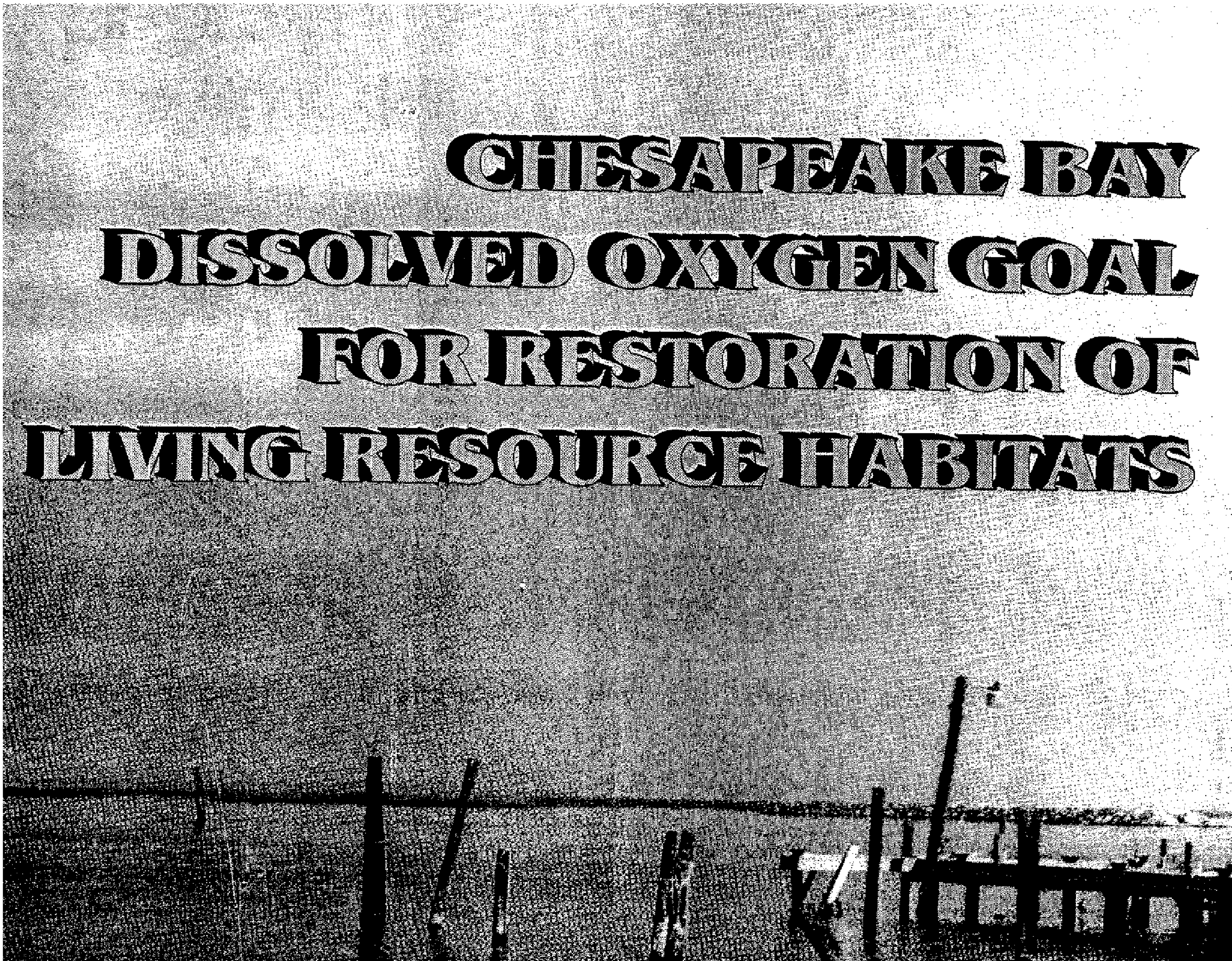
CHESAPEAKE BAY DISSOLVED OXYGEN GOAL FOR RESTORATION OF LIVING RESOURCE HABITATS



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CHESAPEAKE BAY
DISSOLVED OXYGEN GOAL FOR RESTORATION OF LIVING RESOURCE HABITATS

A Synthesis of Living Resource Habitat Requirements with Guidelines for Their Use in Evaluating Model Results and Monitoring Information

DECEMBER 1992

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For the Living Resources Subcommittee
and
The Implementation Committee's
Nutrient Reduction Strategy Reevaluation Workgroup
of the
Chesapeake Bay Program

Reevaluation Report #7c

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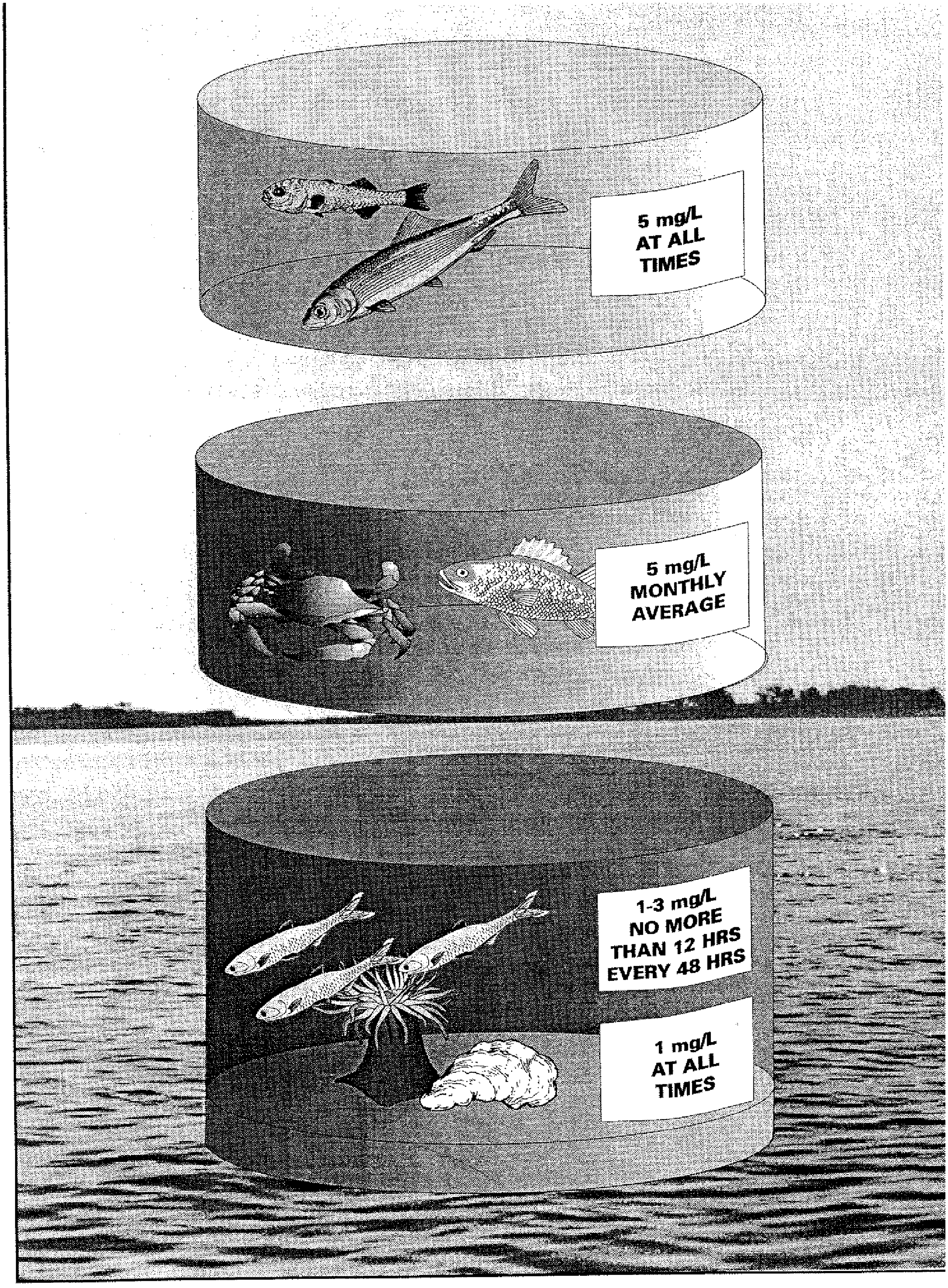
5 mg/L
AT ALL
TIMES
5 mg/L
MONTHLY
AVERAGE
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NO MORE
THAN 12 HRS
EVERY 48 HRS
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AT ALL
TIMES

EXECUTIVE SUMMARY

Overview

The signatories of the 1987 Chesapeake Bay Agreement pledged to manage the Chesapeake Bay as an integrated ecosystem. To that end, goals and commitments were established for living resources and water quality, as well as population growth and development, public information, education and participation, public access, and governance. The living resources and water quality goals of the 1987 Bay Agreement are as follows:

> "provide for the restoration and protection of the living resources, their habitats and ecological relationships," and
>
> "reduce and control point and nonpoint sources of pollution to attain the water quality condition necessary to support the living resources of the Bay."

In support of these goals, the Chesapeake Executive Council (CEC) made commitments to "develop and adopt guidelines for the protection of water quality and habitat conditions necessary to support the living resources found in the Chesapeake Bay system, and to use these guidelines in the implementation of water quality and habitat protection programs," and to "achieve by the year 2000 at least a 40 percent reduction of nitrogen and phosphorus entering the mainstem of Chesapeake Bay." The signatories also agreed "to re-evaluate the 40 percent reduction target based on the results of modeling, research, monitoring and other information."

One tool which has been developed to address the Bay Agreement commitments is the time-variable water quality model, which predicts the effects of particular nutrient load reduction scenarios on water quality. Additional tools include this report, *Chesapeake Bay Dissolved Oxygen Goal for Restoration of Living Resource Habitats,* and the companion document *Chesapeake Bay Submerged Aquatic Vegetation Habitat Requirements and Restoration Targets: A Technical Synthesis* (Batiuk *et al.* 1992). These syntheses are intended to:

- establish living resources-based water quality goals to be used in evaluating model simulation results;
- provide a firm ecological basis for the reevaluation of the *Baywide Nutrient Reduction Strategy* (CEC 1988a);
- provide guidelines that can be used "in the implementation of water quality and habitat protection programs;" and
- establish firmer connections between living resources and restoration of water quality.

The target concentrations of the dissolved oxygen restoration goal in this report are not meant to be enforceable standards for either wastewater discharge permitting or other types of regulatory activities. A state may pursue adoption of these goals as water quality standards using the appropriate administrative process.

The Report

Section I provides an introduction, including background on the need for developing this document, report objectives, and a brief summary of characteristics of dissolved oxygen in Chesapeake Bay. The aquatic animals and plants which make up the Bay ecosystem require dissolved oxygen for respiration. Monitoring data indicates that many areas of the Bay experience sudden or persistent declines in dissolved oxygen, which can adversely affect living resources. Low dissolved oxygen reduces available habitat for all but a few species and may cause stress and mortality in immobile species which are unable to avoid the unsuitable conditions. A major tenet of the Chesapeake Bay Program is that restoring dissolved oxygen to such areas will provide substantial habitat benefits.

Sections II and III in this document establish and defend a dissolved oxygen restoration goal for Chesapeake Bay, based on extensive analysis and evaluation of research data. Dissolved oxygen tolerance information was compiled and interpreted for the 14 target species of fish, molluscs and crustaceans reported in *Habitat Requirements for Chesapeake Bay Living Resources* (Funderburk *et al.* 1991), as well as information published for other benthic and planktonic species, and key investigations recently completed.

bottom habitat and volumes of water are predicted to meet or exceed the applicable target concentrations of dissolved oxygen. For interpretive purposes, the following table defines measures for reaching decisions about suitability, unsuitability and marginality of habitat:

Habitat Condition	Percentage of Time Areas Meet Target Concentrations
Suitable	90-100%
Marginal	50-90%
Unsuitable	Less than 50%

Suitable or acceptable habitat provides satisfactory conditions for survival, growth and reproduction of living resources within the constraints imposed by the formation of density layers. Marginal habitat provides increased opportunities for establishment of benthic invertebrates and foraging by bottom feeding fish. Unsuitable habitat is inhospitable to all but the most tolerant of living resources. We note that what is considered "acceptable habitat" for this purpose is not necessarily fully supportive of living resources requirements for dissolved oxygen. The uncertainties in the analysis and natural variability of the Bay environment compel a more flexible view of habitat suitability than would be dictated by biological considerations alone.

Nutrient reduction scenario results are compared to the "base case" (i.e. existing conditions) model scenario results using this interpretive method. The percent of bottom area or water volume in which habitat quality improves from unsuitable to marginal or from marginal to suitable appears to be the most convenient means of evaluating the living resources benefits for a particular scenario relative to base case or other scenarios.

This interpretive scheme was developed for the particular needs of reevaluating the Nutrient Reduction Strategy. There are other ways to apply the target concentrations of the Chesapeake Bay Dissolved Oxygen Goal for Restoration of Living Resource Habitats to monitoring data and to model output. Work to develop other applications is ongoing.

The Chesapeake Bay Dissolved Oxygen Goal for Restoration of Living Resource Habitats is:

to provide for sufficient dissolved oxygen to support survival, growth and reproduction of anadromous, estuarine and marine fish and invertebrates in Chesapeake Bay and its tidal tributaries by achieving, to the greatest spatial and temporal extent possible, the following four target concentrations of dissolved oxygen, and by maintaining the existing minimum concentration of dissolved oxygen in areas of Chesapeake Bay and its tidal tributaries where dissolved oxygen concentrations are above the recommended targets.

TARGET DO CONCENTRATIONS	TIME AND LOCATION
DO $\geq$1.0 mg/L	ALL TIMES, EVERYWHERE;
1.0 mg/L $\leq$DO $\leq$3.0 mg/L	FOR NO LONGER THAN 12 HOURS, INTERVAL BETWEEN EXCURSIONS AT LEAST 48 HOURS, EVERYWHERE;
MONTHLY MEAN DO $\geq$5.0 MG/L	ALL TIMES, THROUGHOUT ABOVE-PYCNOCLINE WATERS;
DO $\geq$5.0 mg/L	ALL TIMES, THROUGHOUT ABOVE-PYCNOCLINE WATERS, IN SPAWNING REACHES, SPAWNING RIVERS AND NURSERY AREAS.

The pycnocline is the portion of the water column where density changes rapidly because of salinity and temperature

The target concentrations are based on patterns which emerge from examining the best available information. Although a large body of data exists, there remain extensive gaps in our knowledge and therefore, best professional judgement was exercised in making decisions about the precise values of the target concentrations. As research continues in this area, especially on the effects of exposure to fluctuating concentrations of DO, revision of the target concentrations may be appropriate. Appendix A contains details of the literature cited in this synthesis.

Section IV provides applications of the Goal and target concentrations to monitoring and modeling information. Linkages are developed relating complex variability in environmental oxygen concentrations to data from the semi-monthly Baywide monitoring program, and seasona averaged output from the Chesapeake Bay tin variable water quality model. This section expla the relationships developed and how to use them evaluate present and projected dissolved oxyg conditions in the Bay and its tributaries. Appendi contains further details of the statistical appro used in this analysis.

Interpretation

With these tools we can evaluate achievement of t target concentrations for any model cell monitoring station. However, for simplicity presentation on a Baywide basis, it was necessary develop an aggregation scheme. Comparison habitat benefits among nutrient reduction scenar are based on the percentages of time that areas

I. INTRODUCTION

Background

The living resources goal of the 1987 Chesapeake Bay Agreement is to: "provide for the restoration and protection of the living resources, their habitats and ecological relationships." In support of this goal, the Chesapeake Executive Council (CEC) made a commitment to "develop and adopt guidelines for the protection of water quality and habitat conditions necessary to support the living resources found in the Chesapeake Bay system, and to use these guidelines in the implementation of water quality and habitat protection programs."

Habitat Requirements for Chesapeake Bay Living Resources (CEC 1988b) was published in January 1988 in response to this commitment. Thirty target species were selected from a list of 160 representative species and species complexes to represent, either directly or through food chain associations, the Bay's commercially, recreationally, and ecologically important species of fish, shellfish, submerged aquatic vegetation, and wildlife. Although this document was a good start towards defining the conditions necessary to provide suitable habitats for the Bay's living resources, the information was neither complete, nor presented in such a way that it could be used directly in the implementation of water quality restoration programs.

An extensive revision of the original habitat requirements report was completed by a team of scientists who are experts on each of the target species. The objectives of the revised habitat requirements document (Funderburk *et al.* 1991) were to compile all of the available information on habitat requirements of the designated Chesapeake Bay target species, and to synthesize this information in ways that would make it directly useful in water quality management programs. Habitat requirements for dissolved oxygen (DO) identified in Funderburk *et al.* (1991) provided the starting point for the development of the DO restoration goal.

The 1987 Chesapeake Bay Agreement also committed the signatories to "achieve by the year 2000 at least a 40 percent reduction of nitrogen and phosphorus entering the mainstem of Chesapeake Bay" and "to re-evaluate the 40 percent reduction target based on the results of modeling, research, monitoring and other information." The nutrient reduction commitment was based upon the results of a summer-averaged, steady-state water quality model that predicted marginal increases in deep water DO in response to a 40 percent reduction in nitrogen and phosphorus loads to the Bay. As a part of the process of reevaluating the nutrient reduction goal, habitat requirements for nutrients (Batiuk *et al.* 1992) and DO (this report) have been synthesized. These syntheses are intended to: 1) establish living resources-based water quality goals to be used in evaluating model simulation results; 2) provide a firm ecological basis for the reevaluation of the *Baywide Nutrient Reduction Strategy* (CEC 1988a); 3) provide guidelines that can be used "in the implementation of water quality and habitat protection programs;" and 4) establish firmer connections between living resources and restoration of water quality.

Dissolved oxygen is a major factor affecting the survival, distribution, and productivity of living resources in Chesapeake Bay. Much of the deep water of the mainstem Chesapeake Bay becomes anoxic during summer months and is therefore nearly devoid of animal life. Many Chesapeake Bay tributaries experience both episodic and persistent oxygen depletion in summer that results in significant stress to living resources. Model projections which led to the current nutrient reduction strategy for the Bay indicated that reductions in nutrient inputs would result in increased deep-trough DO that would benefit the Bay's living resources. However, neither tributaries, other areas of the mainstem Bay, nor the specific DO requirements of living resources were given consideration at the time, because of the relatively low resolution of the steady-state water quality model, and the limited information available on habitat requirements.

Objectives of this Report

1. Establish a restoration goal for DO with target concentrations sufficient to protect the survival, growth and reproduction of the Bay's living resources.

All of the aquatic animals among the Chesapeake Bay target species - ten species of fish, blue crabs, and three molluscs - require DO for respiration. So do the benthic and planktonic animals and plants which form the food base for the target species. The target species, together with additional representative benthic species of fish and invertebrates for which DO tolerance information was reviewed (Saksena and Joseph 1972; Holland *et al.* 1989; Stickle *et al.* 1989; Stickle 1991; Houde 1991; Miller and Poucher 1991, 1992; Breitburg 1992a, 1992b), represent a wide range of habitats, life history patterns, and tolerances to low DO. Therefore, habitat restoration goals designed to protect the survival, growth, and reproduction of these species should be sufficient to protect other species, and by extension, the Bay's aquatic ecosystem, from harm caused by inadequate concentrations of DO. All of the information on DO tolerances (lethal, sublethal, long term and short term) contained in Funderburk *et al.* (1991) and supplementary references (Appendix A) has been combined and evaluated to develop the DO restoration goal. The target concentrations of the DO Goal in this report are not meant to be enforceable standards for either wastewater discharge permitting or other types of regulatory activities. A state may pursue adoption of these target concentrations as water quality standards using the appropriate administrative process.

2. *Provide a basis for evaluating water quality model results.*
The DO restoration goal presented here will be used to assist in evaluating the results of nutrient load reduction scenarios modeled as a part of the reevaluation of the Baywide Nutrient Reduction Strategy (CEC 1988a). The three-dimensional, time-variable water quality model of the Bay projects concentrations of DO for nine segments (averaged from projections for thousands of model cells) in three depth layers and four seasons based upon varying amounts, timing, and geographical distributions of nitrogen and phosphorus loads delivered to the Bay and its tributaries. Sufficient concentrations of DO to protect living resources will be an important consideration in evaluating options for nutrient reduction.

3. *Ensure that the baywide DO restoration goal is reasonable with respect to natural processes.*
The restoration goal includes target DO concentrations, with limits to the duration and frequency of reoccurrence, which reflect living resources tolerances to low DO. In order to make these requirements comparable with results from the Chesapeake Bay time-variable water quality model, and to ensure that the target requirements are physically reasonable, water quality data from the Chesapeake Bay Monitoring Program and measurements made in greater temporal detail by other sampling programs have been analyzed extensively.

In Section IV, we compare the DO target concentrations to monitoring data from several areas of the Bay, present a hypothetical demonstration of how improvements in DO might translate into fulfillment of the habitat goal, and describe methods for evaluating time-variable model results in comparison to the target concentrations.

Characteristics of Dissolved Oxygen in Chesapeake Bay

To understand how the goal-setting decisions were reached, and the process for making the restoration goal useful for evaluating model results, it is necessary to know something of the complex dynamics of DO in the Bay. The following paragraphs provide a brief overview. For detailed information on DO processes in Chesapeake Bay, see Mackiernan (1987) and Smith *et al.* (1992).

Dissolved oxygen in natural waters has two major sources: 1) atmospheric oxygen which diffuses into the water at the surface, and 2) oxygen which is produced by plants (chiefly free-floating microscopic plants, or phytoplankton) during photosynthesis. Animals, plants and bacteria consume DO by respiration. Oxygen is also consumed by chemical processes (e.g., sulfide oxidation, nitrification). Depletion of DO has harmful effects on animals, and can stimulate production of hydrogen sulfide and ammonia and the release of heavy metals and phosphate from bottom sediments.

The amount of oxygen dissolved in water changes as a function of temperature, salinity, atmospheric pressure, and biological and chemical processes. The equilibrium (or saturated) concentration of DO in natural waters ranges from about 6 to 14 parts per million (or mg/L). The higher the temperature and salinity, the lower the equilibrium DO concentration. Biological processes such as respiration and photosynthesis can affect the concentration of DO faster than new equilibrium can be reached with the atmosphere. As a result, for relatively short periods of time, or under conditions of reduced mixing, DO concentrations can be driven far above or reduced well below saturation. Dissolved oxygen can decrease to near zero (anoxia), especially in deep or stratified bodies of water, or increase as high as about 20 mg/L (supersaturation) in dense algal blooms.

There are seasonal considerations, as well. Low DO in Chesapeake Bay is mostly associated with deep water during the warm months (May-September), when the water column is stratified into density layers with cool salty water at the bottom, and warm, fresher water near the surface. The bottom layer becomes oxygen-depleted because the oxygen consumed by respiration and chemical oxidation cannot be replaced through diffusion of atmospheric oxygen and there is insufficient light to support photosynthetic production of oxygen. Some parts of the Bay can become anoxic for periods of days or weeks during midsummer.

In summer, very low DO can also occur for shorter periods of time (a few hours to a few days) in shallow water. In these cases, DO is depleted by the decay of large amounts of organic matter (perhaps due to respiring or dying algae blooms or from wastewater discharges). Deep water low in oxygen can also be moved into shallow areas by winds. Episodes of strong winds can transport (literally "slosh") water with extremely low oxygen content across the Bay bottom, up and into the habitat of shallow-water dwelling living resources. While strong winds persist, low oxygen waters may remain in the shallows for 40 hours or more. During these times inshore species are continuously exposed to stressful or life-threatening conditions. This sloshing of deep water is sometimes so extreme that anoxic waters move almost to the shoreline. During the resulting "jubilees" or "crab wars," blue crabs and fish congregate at the water's edge attempting to find sufficient oxygen to stay alive (Van Heukelem 1991).

In the spring, striped bass, white perch, shad, herring, and yellow perch spawn far up the Bay's tributaries. The eggs and larvae of these species are quite sensitive to low DO, and could be threatened by even moderate DO depletion associated with algal blooms or wastewater discharges. In the fall and winter, DO depletion is uncommon, and the most sensitive life stages of the target species generally are not present.

Because of the natural fluctuations of DO, and the varied ability of the target species to tolerate less than desirable concentrations, habitat requirements for DO cannot be stated as a single, critical concentration. The sensitivity of each species to low DO depends upon life stage, temperature, salinity, duration of exposure, and perhaps other stress factors (e.g. contaminants), in addition to the absolute concentration of DO. Some species are more tolerant of low DO than others. For example, adult oysters and clams can survive anoxia for days (although growth and reproduction may be impaired) whereas shorter exposures to moderately low DO (below about 3 mg/L) can severely affect the survival and development of fish eggs and larvae.

By selecting conditions acceptable for the reproduction, growth, and survival of a variety of sensitive species, habitat requirements can be established that will also protect the Bay's other living resources. Dissolved oxygen tolerance information was compiled and interpreted for the 14 target species of fish, molluscs and crustaceans reported in Funderburk *et al.* (1991), as well as information reported for other benthic and planktonic species (Appendix A).

Some of the information on the effects of low DO on Chesapeake Bay species was essentially anecdotal, or otherwise of limited usefulness (e.g., in some references the duration of exposure was not reported). Information on long-term and sublethal effects of low DO (e.g., reduced growth and reproductive potential) was scarce, the majority of studies having focused on survival thresholds. Variability within and among studies sometimes limited interpretation of results to a range of responses to low DO for some species. When the data are tabulated in a complete matrix of critical DO concentrations for various life stages of the target species (Figure II-1), there are

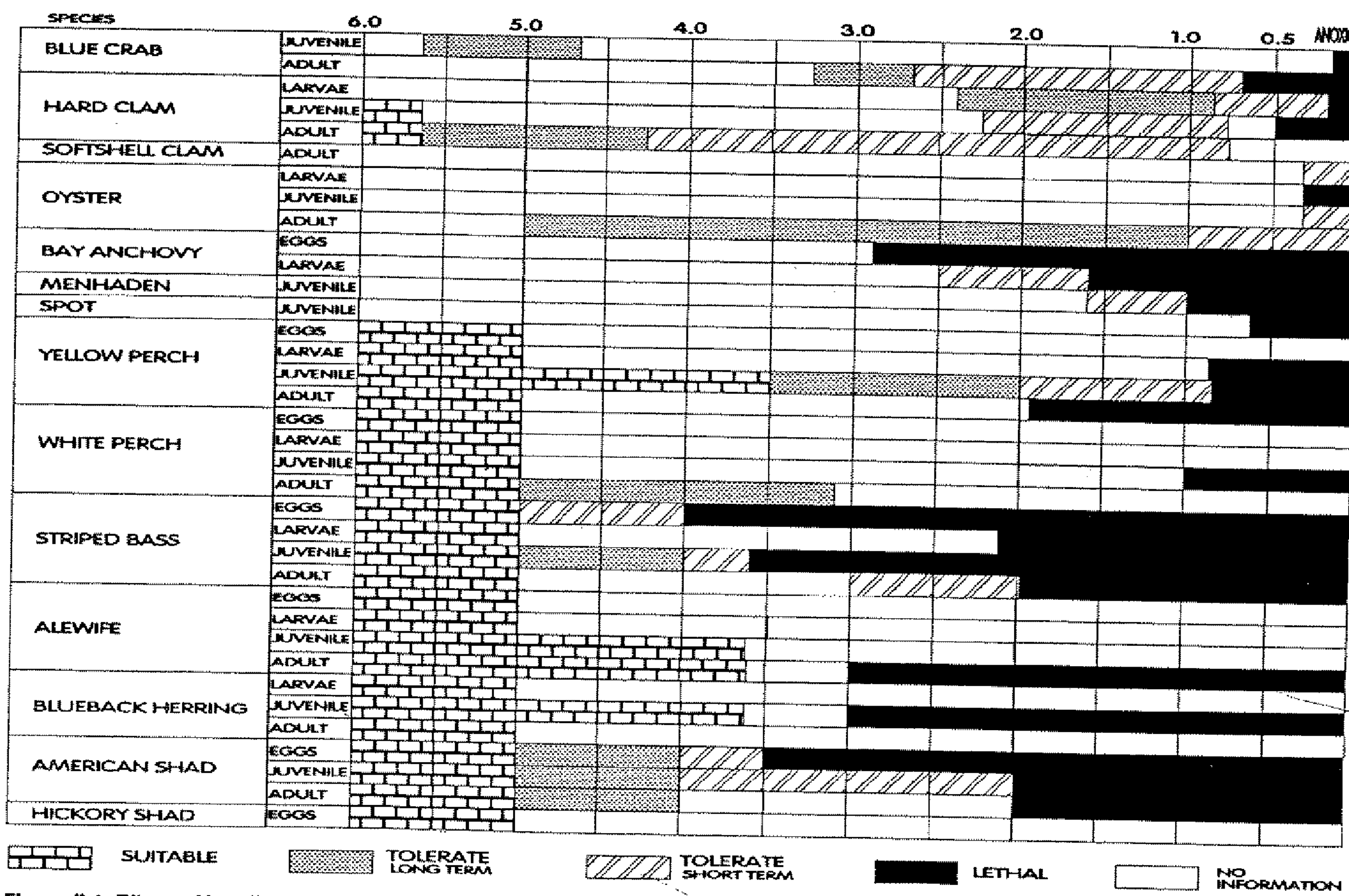

Figure II-1. Effects of low dissolved oxygen on target species, summarized from *Habitat Requirements for Chesapeake Bay Living Resources, 1991 Revised Edition* (Funderburk *et al.* 1991). Note; does not account for temperature, salinity, dissolved oxygen interactions (Appendix A).

many gaps. Ideally, there would be sufficient data available to fully understand the effects of low DO concentrations on each target species as a function of life stage, duration of exposure, temperature, salinity, and significant biological consequences (e.g., mortality, reduced growth and reproduction).

There was, however, enough consistency in the results across the spectrum of target species to identify certain patterns of responses. For example, DO concentrations between zero and near 1.0 mg/L were lethal to all target species that had been tested at these concentrations, with the exception of some molluscs, and to most of the benthic species considered. Another pattern which became apparent was the lack of observed deleterious effects on target species to DO above 5.0 mg/L.

The initial approach for developing the DO restoration goal presumed that DO requirements would vary for different parts of the Bay and for each season, because of the different distributions and tolerances of the target species and the seasonal occurrence of critical life stages. However, DO habitat requirements for the target species (e.g., blue crabs and bay anchovies) that are distributed throughout the tidal waters of the Bay represent the needs of many of the target species except for the eggs, larvae, and juveniles of anadromous fish. This outcome has made the task of developing a DO goal for restoration of living resources habitats more straightforward. It does not, however, preclude regional approaches to management of water quality. When the target concentrations are compared to existing water quality and to the results of model projections, there will undoubtedly be regional differences in the current attainment of the targets and the nutrient load reductions needed to meet them in the future.

III. CHESAPEAKE BAY DISSOLVED OXYGEN RESTORATION GOAL

Basis for the Target Dissolved Oxygen Concentrations

Four target concentrations of DO were identified as necessary to provide sufficient habitat for the survival, growth and reproduction of the Bay's living resources. These DO targets and the rationale for their establishment are outlined below.

Decisions about the precise concentrations of DO, durations, and frequencies included elements of professional judgement, because of the lack of complete information on biological effects of low DO. However, it should be clear from the information presented in Figure II-1 and Appendix A that the recommended concentrations and time scales are reasonable and within the ranges dictated by the available data. We also considered the natural fluctuations of DO and the strong effect on DO of uncontrollable physical processes in the Bay in evaluating whether the recommended DO target concentrations were reasonable as management goals (Section IV). As a result, some of the target concentrations are defined separately for above-pycnocline waters.

Below, the DO target concentrations are defined, accompanied by selected summaries of the literature on species tolerances that was reviewed for development of the DO target concentrations (Appendix A). Illustrations of tolerances are given, with emphasis on the most widely distributed species (Box 1) and biological effects which are likely to be limiting to these species. At the end of this Section, the target concentrations are consolidated into a Chesapeake Bay Dissolved Oxygen Goal for Restoration of Living Resource Habitats.

BOX 1

Target species

Shellfish	
blue crab	*Callinectes sapidus*
eastern oyster	*Crassostrea virginica*
hard clam	*Mercenaria mercenaria*
soft shell clam	*Mya arenaria*
Finfish	
alewife	*Alosa pseudoharengus*
American shad	*Alosa sapidissima*
bay anchovy	*Anchoa mitchilli*
blueback herring	*Alosa aestivalis*
hickory shad	*Alosa mediocris*
menhaden	*Brevoortia tyrannus*
spot	*Leiostomus xanthurus*
striped bass	*Morone saxatilis*
white perch	*Morone americana*
yellow perch	*Perca flavescens*

Other species

Finfish	
naked goby	*Gobiosoma bosci*
skilletfish	*Gobiesox strumosus*
striped blenny	*Chasmodes bosquianus*
winter flounder	*Pseudopleuronectes americanus*
Invertebrates	
amphipod	ampeliscidae
baltic isopod	*Idotea baltica*
copepod	*Acartia tonsa*
ctenophore	*Mnemiopsis leidyi*
grass shrimp	*Palaemonetes pugio, P. vulgaris*
mud crab	*Eurypanopeus depressus*
sand shrimp	*Crangon septemspinosa*
sea nettle	*Chrysaora quinquecirrha*

A. The following target concentration applies to all waters of Chesapeake Bay and its tidal tributaries at all times: 1.0 mg/L DO.

Exposures to DO below 0.5-1.0 mg/L have been found lethal, during some life stage, to all of the target species for which this exposure information is available, except for the molluscs (Figure II-1). Most benthic species also succumb to DO below 0.5-1.0 mg/L eventually, although a number of benthic species survive anoxia for extended periods (Holland *et al.* 1989). Adult soft shell clams can survive near anoxic conditions for up to 7 days (McCarthy 1969) and adult eastern oysters have survived exposure to DO <1.0 mg/L for up to 5 days (Sparks *et al.* 1958). However, 50% of eastern oyster larvae (82 μm) died after 11 hours of exposure to anoxia at 22.0°C and 12 ppt salinity (Widdows *et al.* 1989). Temperature has a critical role in tolerance to low DO concentrations. Adult oysters held at 10, 20 and 30 ppt salinity, had LT_{50} values (days of exposure to anoxia causing 50% mortality) of 28 days at 10°C, 18-20 days at 20°C, and 3-8 days at 30°C (Stickle *et al.* 1989).

Several short term lethal values of DO (1-19 hours) for target species fall within the range of 0.3-1.0 mg/L. The 6-hour LC_{50} for adult blue crabs at 28-30°C is 0.3 mg/L (Carpenter and Cargo 1957). Concentrations of DO below 0.5 mg/L are lethal to adult blue crabs in 4.3 hours at 25°C (Lowery and Tate 1986). The LC_5 and LC_{50} for juvenile spot, in a one hour exposure at 28 C and 6.9 ppt salinity, are 0.6 and 0.5 mg/L DO respectively; the 2-hour LC_5 and LC_{50} for juvenile menhaden, under the same conditions, are 1.0 and 0.7 mg/L (Burton *et al.* 1980). Juvenile white perch experience 40% mortality in 19 hours at 0.5-1.0 mg/L (Dorfman and Westman 1970).

Although adult oysters appear to be tolerant to some degree of anoxia, many species associated with oyster bars are more sensitive to low DO concentrations. Naked goby larvae exposed to ≤0.15, 0.35, and 0.35-0.86 mg/L DO for 1, 2, and 24 hours respectively, suffered 100% mortality (Saksena and Joseph 1972). All new recruits (≤17 mm TL), juveniles, and adult naked gobies survived exposure to 0.75-0.95 mg/L at 25°C for 7 hours; however, there was 100% mortality among new recruits exposed to 0.35-0.60 mg/L DO (Breitburg 1992a). The median tolerance limit (oxygen concentration at which 50% of the larvae would be expected to die after 24 hours) for naked goby, striped blenny and skilletfish are 1.30, 2.50, and 0.72-1.23 mg/L DO (Saksena and Joseph 1972). The 96-hour LC_{50} for adult mud crabs (*Eurypanopeus depressus*), another member of the oyster bar community, is 0.6 mg/L DO (Stickle 1991).

Other common benthic and planktonic species are also sensitive to DO concentrations below 1.0 mg/L. The 6-hour LC_{50} for adult baltic isopods at 10°C is 0.2 mg/L (Theede *et al.* 1969, Theede 1973); the LC_{50} for ampeliscid amphipods in a 96-hour exposure is <0.5 mg/L DO (Miller and Poucher 1991). Sand shrimp have a 96-hour LC_{50} of 1.5 mg/L DO at 20°C and 31 ppt salinity (preliminary data: Miller and Poucher, 1991). The copepod *Acartia tonsa* has a 24-hour LC_{50} of 0.8 mg/L DO (Houde 1991); while the LC_{50} for sea nettles and ctenophores in a 96 hour exposure are 0.7 and 1.0 mg/L DO respectively (Houde 1991).

In addition to direct lethal effects, exposure to DO concentrations <1.0 mg/L can adversely affect the growth and behavior of organisms. Breitburg (1992a) found that male naked gobies abandoned the nest or shelter at DO concentrations of 0.15-0.6 mg/L, and that embryo development time was significantly slowed by repeated exposure to low DO concentrations (Appendix A).

Although DO as low as 1.0 mg/L is never desirable, brief excursions down to 1 mg/L in some deep areas of the Bay should not have severe adverse effects on populations of either target species or benthos. Even an hypoxia-sensitive species (adult alewife) can endure a 5-minute exposure to DO of 0.5 mg/L if escape to an area of higher DO concentration is available (Dorfman and Westman 1970).

B. The following target concentration applies to all waters of Chesapeake Bay and its tidal tributaries at all times: 12-hour maximum duration of DO between 1.0 and 3.0 mg/L, 48-hour minimum return frequency of DO ≤3.0 mg/L and ≥1.0 mg/L.

Bay anchovy eggs hatch in 18-24 hours, and hatching success declines significantly below 3.0 mg/L DO (Chesney and Houde 1989). Houde and Zastrow (1991) suggested that DO <3.0 mg/L limits the viability and productivity of bay anchovy in Chesapeake Bay.

There was no mortality of adult blue crabs in 7-day exposures at about 3.0 mg/L, and less than 20% mortality in a 25-day exposure at 21-23°C (deFur *et al.* 1990). The blue crab is often considered an hypoxia-tolerant species, however, long term exposures to mild hypoxia at high temperatures may be lethal (Stickle *et al.* 1989); tolerance is very temperature dependent (Carpenter and Cargo 1957). Crabs died in pots at ~30°C and ~2.5 mg/L DO (Carpenter and Cargo 1957).

Several target species experienced deleterious effects in exposures to less than approximately 3.0 mg/L, e.g., growth of yellow perch juveniles is reduced at 20°C and DO <2.0 mg/L, but is not affected at DO >3.5 mg/L (Carlson *et al.* 1980). Dissolved oxygen <3.0 mg/L caused mortality in striped bass juveniles (Krouse 1968; Chittenden 1972) and stress in adult striped bass (Chittenden 1972; Coutant 1985). Juvenile blueback herring and adult alewife exposed to 2.0-3.0 mg/L DO for 16 hours experienced 33% mortality (Dorfman and Westman 1970).

Adult white perch avoided waters with DO <35% saturation (~3.2 mg/L), over a temperature range of 8-21°C and salinity range of 2.5-12.5 ppt (Meldrim *et al.* 1974). However, there is evidence that juvenile blueback herring are unable to detect and avoid waters with low DO concentrations (Dorfman and Westman 1970). Dissolved oxygen concentrations <3.0 mg/L blocked migrations of juvenile and adult American shad (Miller *et al.* 1982).

Recent research has established 96-hour LC_{50} values between 1.0 and 3.0 mg/L DO for several species found throughout the Bay (Appendix A). For example, the 96-hour LC_{50} for juvenile and adult sand shrimp, at 20°C and 31 ppt salinity, is 1.5 mg/L (preliminary data: Miller and Poucher 1991); the 96-hour LC_{50} values for larval, and juvenile or adult grass shrimp (*Palaemonetes pugio*) are 1.9 and 1.6 mg/L DO (Stickle 1991). Winter flounder eggs, larvae, and juveniles have 96-hour LC_{50} values of 1.9, 1.5, and 1.4 mg/L DO respectively (Miller and Poucher 1991).

All target species appear to tolerate DO of 3.0 mg/L for short periods of time (Figure II-1; Appendix A). The recommended return frequency, in combination with the protection provided under the 1.0 mg/L instantaneous target concentration, will permit ample periods of time for hatching of anchovy eggs, probably will protect blue crabs trapped in pots for periods of up to a few days, and will prevent frequent recurrences of stressful conditions for other target species. However, recent data indicate that excursions between 1.0 and 3.0 mg/L DO for up to 12 hours may not be fully protective of every Bay species. The time to 50% mortality of larval grass shrimp (*P. vulgaris*) exposed to 1.4 and 1.6 mg/L DO was 2.9 and 21.6 hours respectively (preliminary data: Miller and Poucher 1992).

C. The following target concentration applies to all above-pycnocline waters of Chesapeake Bay and its tidal tributaries: 5.0 mg/L DO monthly average.

This concentration appears to be protective of all target species. Optimum DO for hard clam burrowing rates was somewhat higher than 5.0 mg/L (Savage 1976). Growth rates of hard clams were greatly reduced below 4.2 mg/L (Morrison 1971); DO <5.0 mg/L was considered stressful for this species (Hamwi 1968, 1969; Roegner and Mann 1991).

One study cited found a 50% mortality of juvenile blue crabs in a 28-day exposure to 5.65 mg/L DO at 30°C (Stickle *et al.* 1989). However, long-term exposure to a temperature of 30 C or above is uncommon in Chesapeake Bay. At lower temperatures (21-23°C), there was some mortality of adult crabs in 23-25 day exposures to DO of about 3 mg/L (deFur *et al.* 1990).

Dissolved oxygen ≥5.0 mg/L is a requirement for several species of anadromous fish (Bogdanov *et al.* 1967; Miller *et al.* 1982; ASMFC 1987; Jones *et al.* 1988; Piavis 1991). Miller *et al.* (1982) considered DO concentrations <5.0 mg/L sublethal to juvenile and adult American shad, while Piavis (1991) concluded that a DO of 5 mg/L was the lowest average concentration that sustains normal development and activity for yellow perch. Jones *et al.* (1988) listed 5.0 mg/L as the minimum DO concentration required for all life stages of American and hickory shad, striped bass, white perch and yellow perch; the minimum required for eggs, larvae, subadults and adults of alewife and blueback herring; and the probable minimum for adult menhaden and the egg, larval and juvenile life stages of spot.

Field observations suggest that juvenile spot prefer DO >4.0-5.0 mg/L (Ogren and Brusher 1977; Rothschild 1990) and adult spot are most abundant where DO is >4.0 mg/L (Markle 1976; Chao and Musick 1977; Rothschild 1990). Dissolved oxygen concentrations of 4.0-5.0 mg/L appear to be a minimum for juvenile and adult American shad (Burdick 1954; Jessop 1975), whereas other anadromous species prefer higher concentrations. White perch and striped bass concentrate in areas of at least 6.0 mg/L DO (Rothschild 1990), and adult blueback herring were never captured at sampling stations where DO was <6.0 mg/L (Christie *et al.* 1981).

In general, the 5.0 mg/L monthly mean target concentration, in combination with target concentrations *A* and *B*, should protect all species (except the anadromous fish, see *D*, below) against severe long term stress, and the monthly mean presumably would represent substantial periods with DO above 5.0 mg/L. Dissolved oxygen <6.0 mg/L may cause avoidance or minor sublethal stress in a few species, and may combine with very high water temperatures (≥30°C) to cause more severe stress or mortality.

D. This target DO concentration applies to anadromous fish spawning and nursery areas (Figure III-1) in the above-pycnocline waters of Chesapeake Bay and its tidal tributaries at all times: 5.0 mg/L DO.

This target DO concentration was selected to protect the early life stages of striped bass, white perch, alewife, blueback herring, American shad, hickory shad, and yellow perch. This concentration of DO will allow eggs to hatch normally (Bradford *et al.* 1968; O'Malley and Boone 1972; Marcy and Jacobson 1976; Harrell and Bayless 1981; Jones *et al.* 1988;), as well as allow survival and growth of larval and juvenile stages of all anadromous target species (Tagatz 1961; Bogdanov *et al.* 1967; Krouse 1968; Bowker 1969; Chittenden 1969, 1972, 1973; Meldrim *et al.* 1974; Rogers *et al.* 1980; Miller *et al.* 1982; Coutant 1985; ASMFC 1987; Jones *et al.* 1988). For example, concentrations of DO below 5 mg/L for any duration will not support normal hatching of striped bass eggs (O'Malley and Boone 1972). Although one hatchery operation was able to maintain striped bass fingerlings at DO concentrations of 3-4 mg/L (Churchill

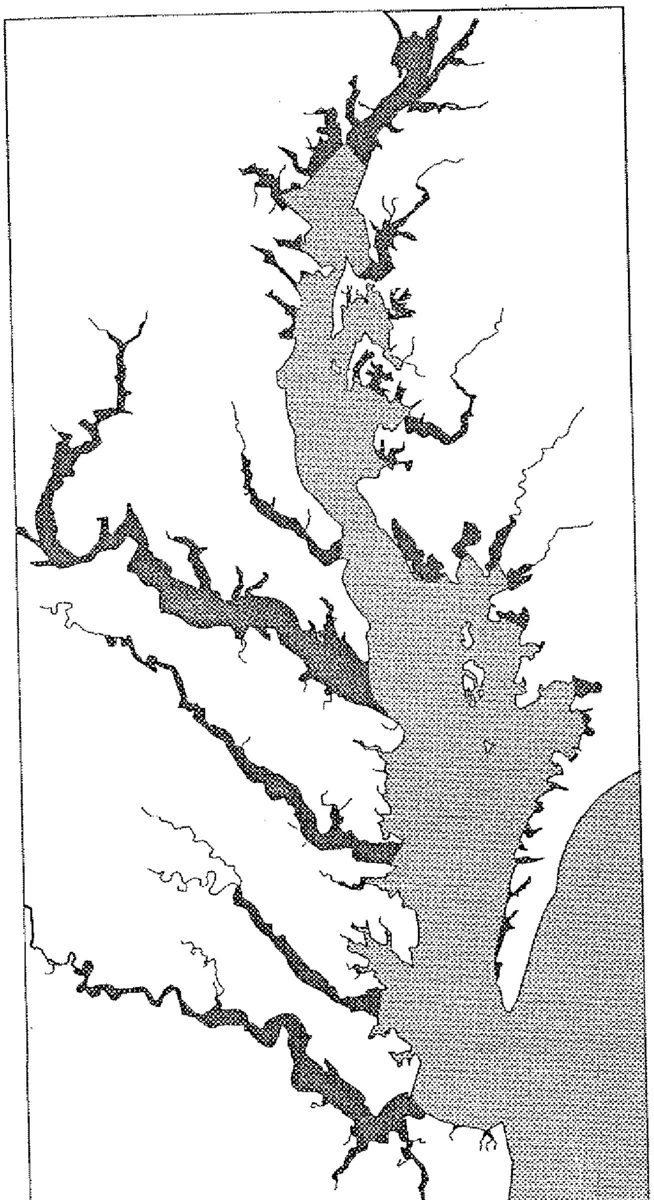

Figure III-1. Habitat distribution of anadromous fish spawning reaches, spawning rivers and nursery areas in Chesapeake Bay (▩); combined for striped bass, white perch, alewife, blueback herring, American shad, hickory shad, and yellow perch (Source: Funderburk *et al.* 1991)

1985; Loos 1991), Bowker *et al.* (1969) found DO >3.6 mg/L required for survival of juveniles.

This target concentration appears to be a critical value for providing acceptable protection for anadromous fish. Dissolved oxygen concentrations above 5 mg/L are within the suitable range for eggs, larvae, and juveniles of yellow perch, white perch, striped bass, alewife, blueback herring, American shad, and hickory shad (Figure II-1). Several authors have indicated that DO ≥5.0 mg/L is a "suitable" or "recommended" level for early life stages of the anadromous species (Bogdanov *et al.* 1967; Krouse 1968; Miller *et al.* 1982; ASMFC 1987; Jones *et al.* 1988; Piavis 1991). Juvenile anadromous species are no more tolerant of low DO than eggs or larvae. Jones *et al.* (1988) listed 5.0 mg/L as the minimum DO concentration required for all life stages, including juveniles and adults, of American and hickory shad, striped bass, white perch and yellow perch. Miller *et al.* (1982) consider DO concentrations <5.0 mg/L sublethal to juvenile and adult American shad. A DO concentration of 5.0 mg/L is also the minimum required for eggs, larvae, subadults and adults of alewife and blueback herring (Jones *et al.* 1988). Because the juvenile anadromous species use the lower estuarine reaches of the spawning rivers as nursery areas, and they are present throughout the year, the 5.0 mg/L target concentration applies to the entire above pycnocline tidal area of the spawning rivers (Figure III-1) over all seasons.

Some field observations have indicated that juveniles and adults of anadromous species prefer DO of ≥6.0 mg/L (Hawkins 1979; Christie *et al.* 1981; Rothschild 1990). However, no lethal or sublethal effects other than possible avoidance have been documented for DO concentrations between 5.0 and 6.0 mg/L.

Chesapeake Bay Dissolved Oxygen Restoration Goal
In combination, the four target DO concentrations provide a DO restoration goal for Chesapeake Bay that reflects the habitat needs of the Bay's living resources (Box 2). Applied individually, achievement of the target concentrations would ensure sufficient habitat quality for survival (1 mg/L and 3 mg/L target concentrations) and continued growth and reproduction (5 mg/L anadromous spawning river and 5 mg/L monthly mean target concentrations). Applied as a single, integrated restoration goal, achievement of all the target concentrations, along with a provision (e.) to ensure that the target concentrations are not construed as allowing degradation where present conditions are adequate, will "provide for sufficient dissolved oxygen to support survival, growth and reproduction" of the Chesapeake Bay's aquatic living resources.

BOX 2

CHESAPEAKE BAY DISSOLVED OXYGEN GOAL FOR RESTORATION OF LIVING RESOURCE HABITATS

GOAL: To provide for sufficient dissolved oxygen to support survival, growth and reproduction of anadromous, estuarine and marine fish and invertebrates in Chesapeake Bay and its tidal tributaries by achieving, to the greatest spatial and temporal extent possible, the following target concentrations of dissolved oxygen:

a) dissolved oxygen concentrations of at least 1.0 mg/L at all times throughout Chesapeake Bay and its tidal tributaries, including subpycnoline[1] waters;

b) dissolved oxygen concentrations between 1.0 and 3.0 mg/L should not occur for longer than 12 hours and the interval between excursions of dissolved oxygen between 1.0 and 3.0 mg/L should be at least 48 hours throughout Chesapeake Bay and its tidal tributaries, including subpycnocline waters;

c) monthly mean dissolved oxygen concentration of at least 5.0 mg/L throughout the above-pycnocline waters of Chesapeake Bay and its tidal tributaries; and

d) dissolved oxygen concentrations of at least 5.0 mg/L at all times throughout the above pycnocline waters of anadromous fish spawning reaches, spawning rivers and nursery areas[2] of Chesapeake Bay and its tidal tributaries as defined in *Habitat Requrements for Chesapeake Bay Living Resources, 1991 Revised Edition;*

and

e) by maintaining the existing minimum concentration of dissolved oxygen in areas of Chesapeake Bay and its tidal tributaries where dissolved oxygen concentrations are above those stated in a) through d).

[1]The pycnocline is the portion of the water column where density changes rapidly because of salinity and temperature differences. See Appendix B for definitions

[2]Spawning reaches, spawning rivers, and nursery areas are presented in Figure III-1.

IV. APPLICATION OF MONITORING AND MODELING INFORMATION

Introduction

In this section, examples of DO dynamics observed in different Bay habitats are examined in light of the target DO concentrations. An approach is presented for using data from the Chesapeake Bay Monitoring Program both to monitor progress toward the restoration goal and to evaluate improvements in DO which are projected by the Chesapeake Bay time-variable water quality model.

Dissolved Oxygen Variability in the Environment

Recent studies have produced relatively long-term, semicontinuous (5 to 30-minute sampling interval) records of bottom DO concentrations in a variety of Chesapeake Bay environments. Data from three sites representative of major Bay subsystems are shown in Figure IV-1. The July-August period covered by these records is when DO deficiency is greatest and maximum stress to living resources typically occurs. These data demonstrate the large, but typical, variations in DO to which organisms are exposed over short time periods (hours to days). These data also show the variability in the duration and frequency of exposure to low DO within and among sites.

Dissolved oxygen data from an 18-meter deep water habitat in the stratified and strongly tidal lower reaches of the York River estuary are shown in Figure IV-1a (data courtesy of R. Diaz, Virginia Institute of Marine Science). Dissolved oxygen concentrations at this site are summarized below (Table IV-1). This deployment was below the pycnocline, so the 5-mg/L monthly mean and anadromous fish target concentrations of the goal do not apply; the latter concentrations are shown in Tables IV-1 and IV-2 only to illustrate the habitat conditions at these sites.

Table IV-1. Distribution of DO concentrations during July and August 1989 in the Lower York River (18 m).

July mean: 3.0 mg/L August mean: 1.7 mg/L
<5 mg/L: 98% of the time <3 mg/L: 74% of the time <1 mg/L: 14% of the time
15 events <3mg/L ≥12 hours; 2 events <3mg/L lasted for 6-7 days; 70 events where DO <3mg/L returned within 48 hrs.

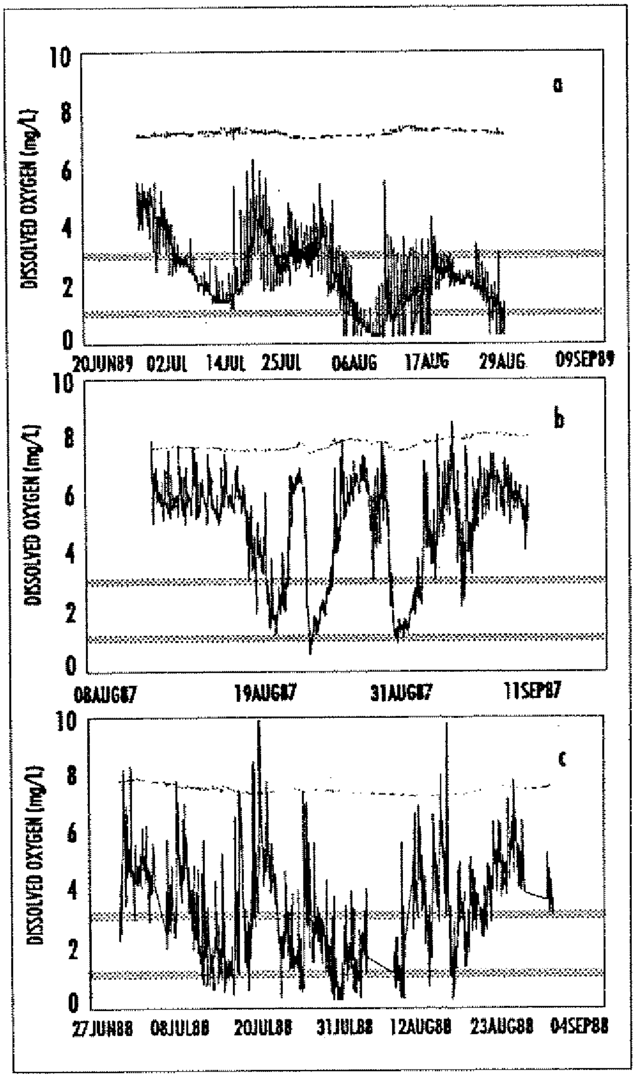

Figure IV-1. Semicontinuous dissolved oxygen measurements at three sites in Chesapeake Bay. Upper line is the saturation concentration of dissolved oxygen; bottom line is observed dissolved oxygen. 1 and 3 mg/L reference lines.

a. York River: sensor depth 18 m, July 1 to August 31, 1989 (Diaz *et al.* in press).

b. Mainstem, near Choptank River mouth; sensor depth 13 m, August 12 to September 9, 1987 (Sanford *et al.* 1990).

c. St. Leonard Creek; sensor depth 3-4 m, July 1 to August 31, 1988 (Maryland Department of the Environment).

Dissolved oxygen was monitored semicontinuously during the summer at a depth of 13 m near the mouth of the Choptank River (Figure IV-1b; data courtesy of L. Sanford, University of Maryland). This location is representative of bottom habitats near the

Table IV-2. Distribution of DO concentrations in August and September 1987 off the mouth of the Choptank River (13 m).

28-day mean: 4.7 mg/L
<5 mg/L: 41% of the time
<3 mg/L: 22% of the time
<1 mg/L: slightly <1% of the time
3 events <3mg/L lasted 12 hours or longer;
8 events where DO <3 mg/L returned within 48 hrs.

usual depth of the pycnocline. The DO characteristics are summarized in Table IV-2. This deployment was below the pycnocline for portions of the period of record.

Tributary creeks a few meters deep also can experience low DO conditions during summer. Figure IV-1c shows DO concentrations in waters overlying a natural oyster bar 3-4 m deep along St. Leonard Creek, a tidal tributary of the Patuxent River (data courtesy of R. Summers, Maryland Dept. of the Environment). The DO characteristics at this site are summarized in Table IV-3.

Table IV-3. Distribution of DO concentrations in July and August 1988 in St. Leonard Creek (3-4 m).

July mean: 3.2 mg/L
August mean: 3.3 mg/L
<5 mg/L: 87% of the time
<3 mg/L: 46% of the time
<1 mg/L: 9% of the time
15 events <3mg/L lasted ≥12 hours;
64 events where DO <3mg/L returned within 48 hrs.

Cumulative frequency (in this case, cumulative percentage) distributions constructed from all DO observations at a site are one means of comparing complex patterns among different locations. Although they are simple and instructive measures of variability, cumulative frequency distributions do not explicitly take into account the frequency or duration of exposure to deleterious oxygen concentrations. The plots in Figure IV-2 show the range of the m ments and what percent of the measuremen below a given concentration.

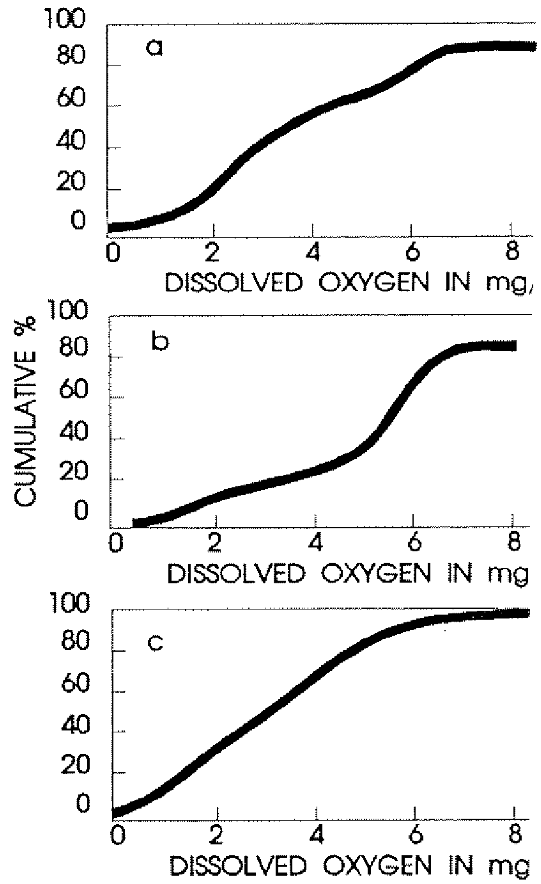

Figure IV-2. Cumulative frequency distributions deve semicontinuous dissolved oxygen data at the three sitc Figure IV-1.
a. York River
b. Mainstem near Choptank River mouth
c. St. Leonard Creek

The three semicontinuous DO data sets were to portray DO characteristics in three differe peake Bay habitats. One important qu whether these patterns of variation are char of similar habitats in other parts of the Bay do similar habitats have similar DO "signatu is the pattern at a location generally similar f to year under similar climatic conditions? deviations from the patterns observed so fa expected, but additional work in this area way and planned for the future by severa ating programs.

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The Chesapeake Bay Monitoring Program and the Time-Variable Model

Semicontinuous DO data are valuable to our knowledge of physical processes, for calibration and interpretation of low frequency monitoring data, and in translating habitat requirements into realistic management goals. But these high frequency data sets are costly to acquire and not yet available from enough sites or time periods either for Baywide assessment of present conditions or for measuring progress toward the DO restoration goal. Therefore, the primary source of DO data for these assessments is the Chesapeake Bay Monitoring Program, which began in 1984.

Dissolved oxygen is one of a suite of water quality parameters measured at the network of stations throughout the Bay. The water quality monitoring stations and the Chesapeake Bay Program segmentation scheme are shown in Figure IV-3. Depth profiles of DO are collected at each station twice a month from spring through summer and once a month in fall and winter.

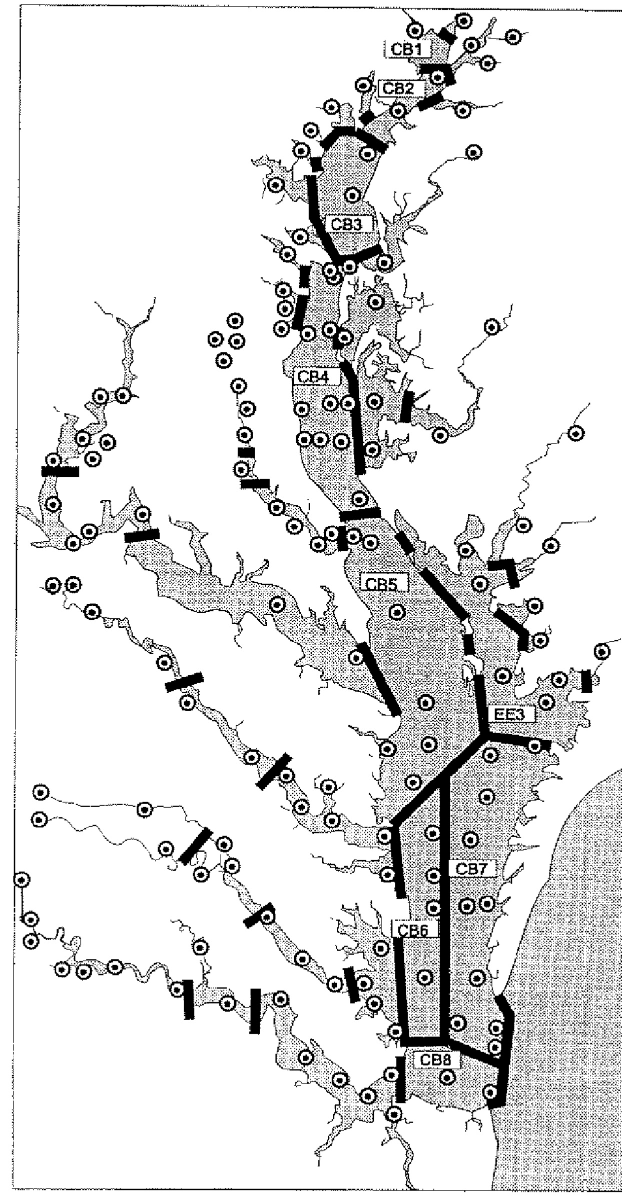

Figure IV-3. Chesapeake Bay mainstem and tributary water quality monitoring stations (⊙) with the Chesapeake Bay Program segmentation scheme shown (lines). Mainstem segments are labeled.

Another means of evaluating DO conditions is the Chesapeake Bay time-variable water quality model. This computer model was developed to forecast the effects of particular nutrient load reduction scenarios on water quality, e.g., the effect of nutrient load reductions on DO concentrations. For purposes of the model, the Bay is divided spatially into several thousand three-dimensional blocks or "cells." Temporally, the mathematical modelling process makes water quality projections for each cell at time steps of a few hours. However, for evaluating model-projected water quality responses, each nutrient reduction scenario provides an estimate of the average seasonal DO concentration for each cell. Shorter time intervals (e.g., monthly, daily) may be available in the future. For calibration and reporting purposes, the cells are averaged into nine segments along the planar (surface) axis of the Bay and into three vertical (depth) layers (Figure IV-4). The depth layers are defined relative to the pycnocline, the region in the water column where separation occurs between the more buoyant, fresher surface waters, and denser, saltier bottom waters (see Appendix B for further discussion of the pycnocline).

The DO restoration goal specifies limits on durations and frequency of reoccurrence of DO below the target concentrations; monitoring data and model projections do not have sufficient temporal resolution to evaluate conformance with these limits. Therefore, relationships must be defined among 1) the DO restoration goal target concentrations, 2) the real-time semicontinuous DO measurements, 3) the twice-monthly Bay Monitoring Program data, and 4) the seasonal means projected by the time-variable model.

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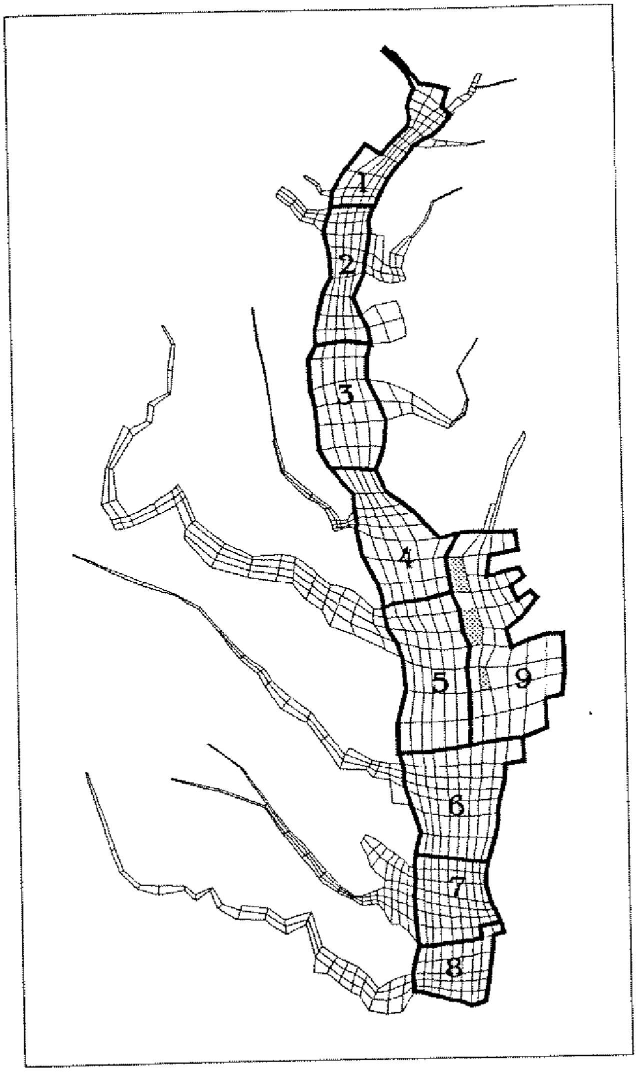

Figure IV-4. Grid for the Chesapeake Bay time-variable model. Only surface model cells are shown. Dark lines and numbers refer to model segments.

Bay Monitoring and Semicontinuous Data Comparisons

As a first step, DO data collected through the Monitoring Program were compared with semicontinuous DO data. The Choptank River data set illustrated in Figure IV-1b is one of five such data records that were collected simultaneously at separate sites along a cross-Bay transect in the middle region of the mainstem Bay (Figure IV-5). Dissolved oxygen was monitored at approximately 6, 13, and 19 m at three locations, and at both 6 and 9 m at a fourth location. These sites were in the vicinity of monitoring stations in Chesapeake Bay Program segment CB4 (Figure IV-5) which were visited on two monitoring cruises during the four-week deployment of the continuous recorders.

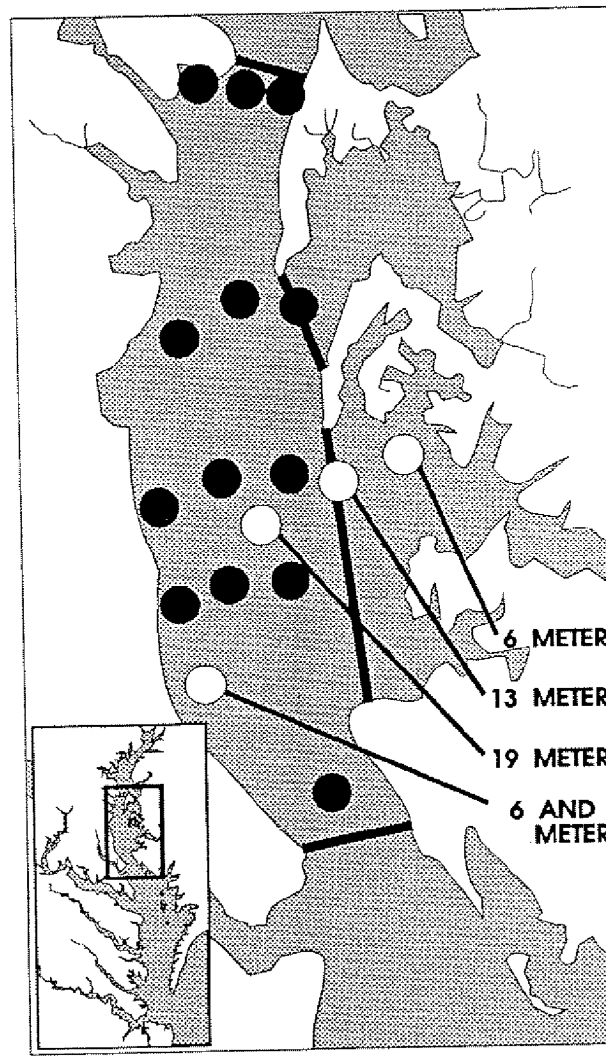

Figure IV-5. Location of semicontinuous dissolved oxygen sen (○) and selected twice-monthly bay program monitoring stat (●) in segment CB4 (enlargement). Depth of sensor rec discussed in text is indicated.

Dissolved oxygen profiles from the Monitor Program stations in CB4 were plotted together w the means, ranges and standard deviations of semicontinuous DO data (Figure IV-6). Because deployed oxygen sensors made 4-12 measurem per hour, 24 hours a day over many days, they w more likely to encounter and record ephem extreme conditions. As expected, therefore, minimum and maximum values of the semicor uous data are outside the ranges of the Monito Program data. The other summary statistics of Bay Monitoring Program and semicontinuous c however, are generally comparable, with the ex tion of the 13-m depth (Figure IV-6 and Table I

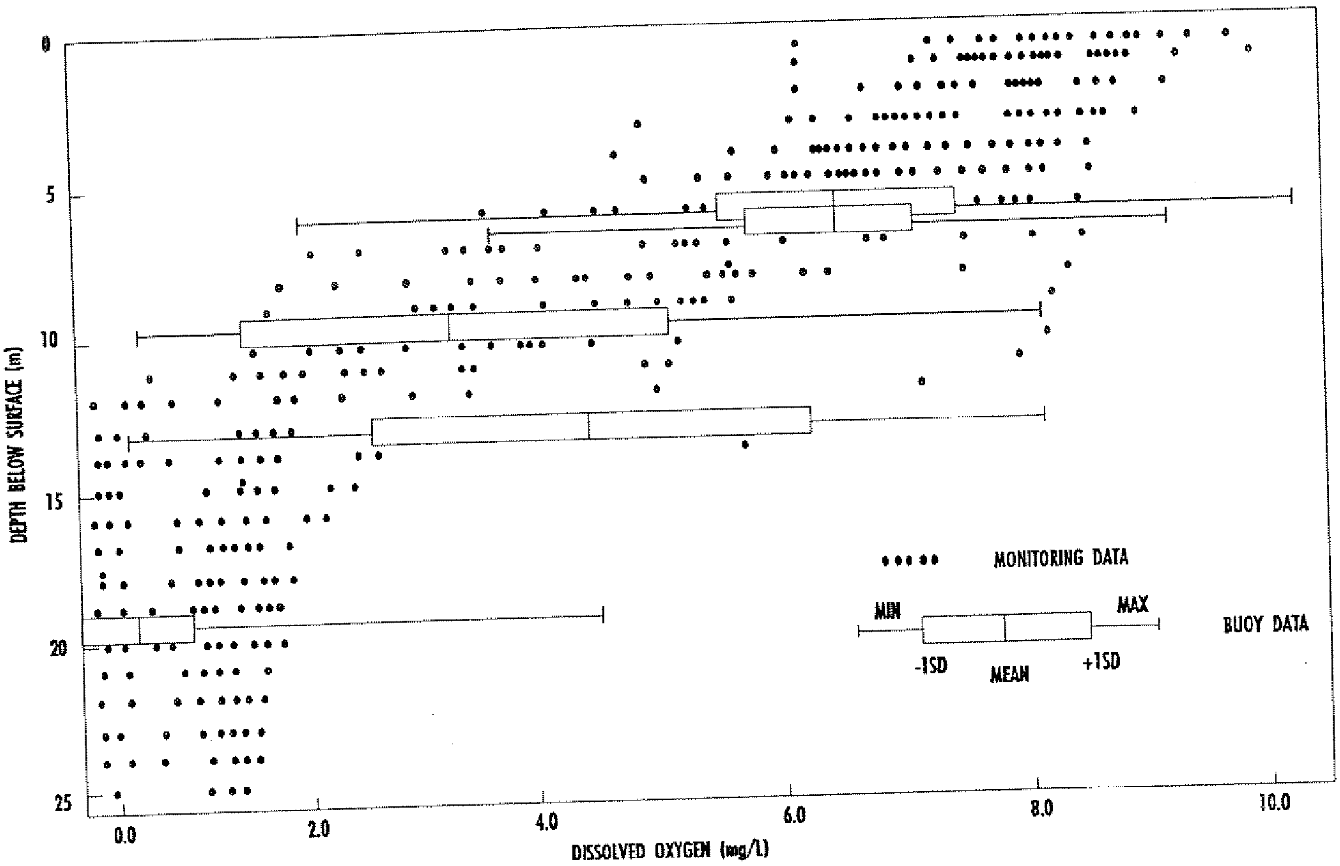

Figure IV-6. Comparison of Monitoring Program and semicontinuous dissolved oxygen data. The observed dissolved oxygen values from mainstem monitoring program stations in segment CB4 are overlain with plots of the mean, range, and standard deviation of values recorded during the same period by semicontinuous dissolved oxygen monitoring devices in CB4 at the depths shown.

At the 13-m depth, all the statistics are higher in the semicontinuous data than in the twice-monthly Monitoring Program data. The statistics are higher even than those of the semicontinuous data from the shallower 9-m western shore site. The difference is probably best explained by the bottom geometry of the 13-m location. A shallow sill lies at the mouth of the Choptank River inhibiting intrusion of below-pycnocline waters from the mainstem under typical energy conditions. Sanford *et al.* (1990) note that tidal markers identified in the other buoy data records were not seen in the 13-m data record.

The semicontinuous and Monitoring Program DO data also can be compared by means of cumulative frequency distributions (Figure IV-7). Cumulative frequency plots are particularly useful in showing the extent to which minimum levels of DO may or may not be underestimated by the lower sampling frequency of the Monitoring Program.

In these comparisons, the data collected at depths above and below the region of the pycnocline show close agreement in the percentage of observations at the lower end of the distribution where the stressful DO values lie. For example, at 6 m (Figure IV-7a,b), the percentage of observations less than or equal to 1 mg/L was less than 1% and the percentage less than or equal to 3 mg/L was less than 5%, in both the Monitoring Program and semicontinuous data sets. At 19 m, 98% of the DO observations were less than or equal to 1.6 mg/L in both the Monitoring Program and semicontinuous data sets, and 100% and 99%, respectively, were less than or equal to 3 mg/L (Figure IV-7e).

Whether all Chesapeake Bay mainstem and tributary segments are equally well represented by the number and location of Monitoring Program stations is not completely known. However, based on the example above and additional monitoring and research

Table IV-4. Comparison of semicontinuous (C) and Monitoring Program (M) dissolved oxygen data. The time period for semicontinuous data was August 13 through September 6, 1987; Monitoring Program cruise dates were August 16 and September 2, 1987. N = number of observations.

	N		Mean		Std. Dev.		Minimum		Maximum	
	C	M	C	M	C	M	C	M	C	M
Depth (m)										
6[1]	2270	47	6.5	6.3	0.9	1.5	0.5	2.0	9.9	8.6
6[2]	2443	47	6.7	6.3	1.1	1.5	1.9	2.0	9.8	8.6
9[2]	2443	39	3.8	4.2	2.1	1.5	0.0	1.4	8.1	8.3
13[3]	2422	30	4.6	1.7	1.7	1.4	0.4	0.1	8.1	6.3
19[4]	2435	17	0.5	0.8	0.5	0.5	0.0	0.1	4.4	1.6

[1] Choptank River, 12-min. intervals
[2] West side of main Bay, 5-min. intervals
[3] Choptank River mouth, 5-min. intervals
[4] Mid-channel main Bay, 15-min. intervals

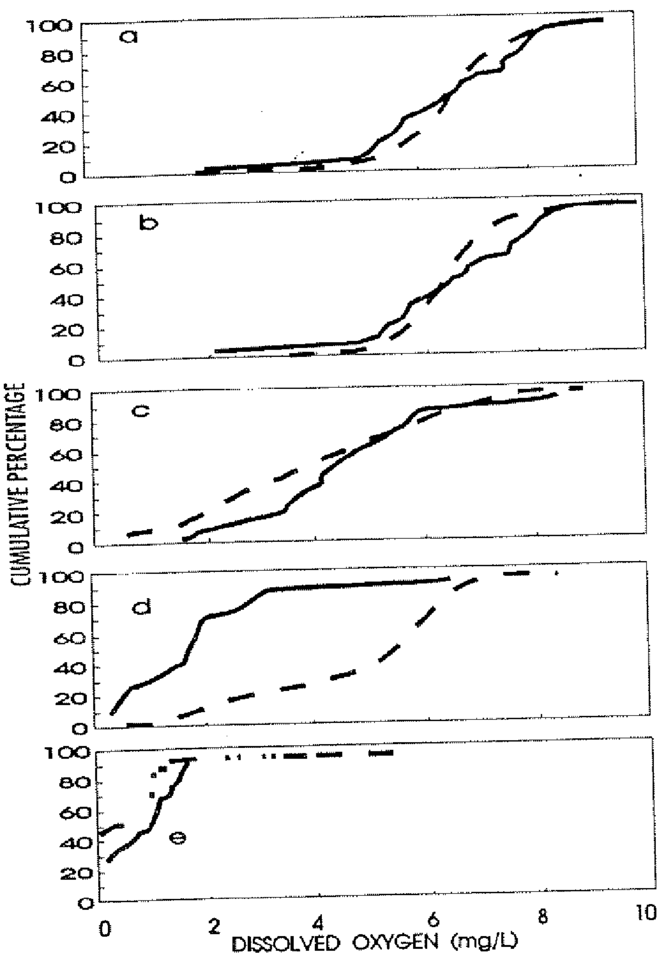

Figure IV-7. Cumulative frequency distributions of semicontinuous dissolved oxygen data (---) and twice- monthly Monitoring Program data (—) for locations in Figure IV-5.
a. 6 meters - west side
b. 6 meters - Choptank
c. 9 meters
d. 13 meters
e. 19 meters

evidence (e.g., Sanford and Boicourt 1990a; 1990 was assumed that the distribution of the Monitc Program data represent the range and ce tendency of real-time DO conditions and that distributions of the twice-monthly monitoring can be applied in evaluating both the Bay's cu status and progress toward the DO restoration {

A Method for Evaluating Progress Toward Restoration Goal

The DO data from the Monitoring Program examined to develop simple methods for evalu different regions of the Bay with respect to th restoration goal's target concentrations. Method also could be applied or adapted to evaluating variable model output were most desirable. Bec model results are seasonal mean concentration seasonal mean DO was chosen as the variab interest. The relationships of the seasonal mean minimum DO concentrations, 2) the standard d tion of DO measurements, and 3) the percenta observations above or below the restoration { target concentrations were explored as po measures of status and progress.

The relationship between the seasonal mean ar percentage of monitoring measurements above concentrations proved to be strong and w applicable in regions of the Bay where DO ob tions ranged above and below the restoratior target concentrations. For example, Figure IV-8 s the relationship for the 1 mg/L, 3 mg/L, monthly mean of 5 mg/L target concentratic segment CB4. The 5 mg/L instantaneous concentration for anadromous fish spawnin nursery habitats does not apply in this segmer

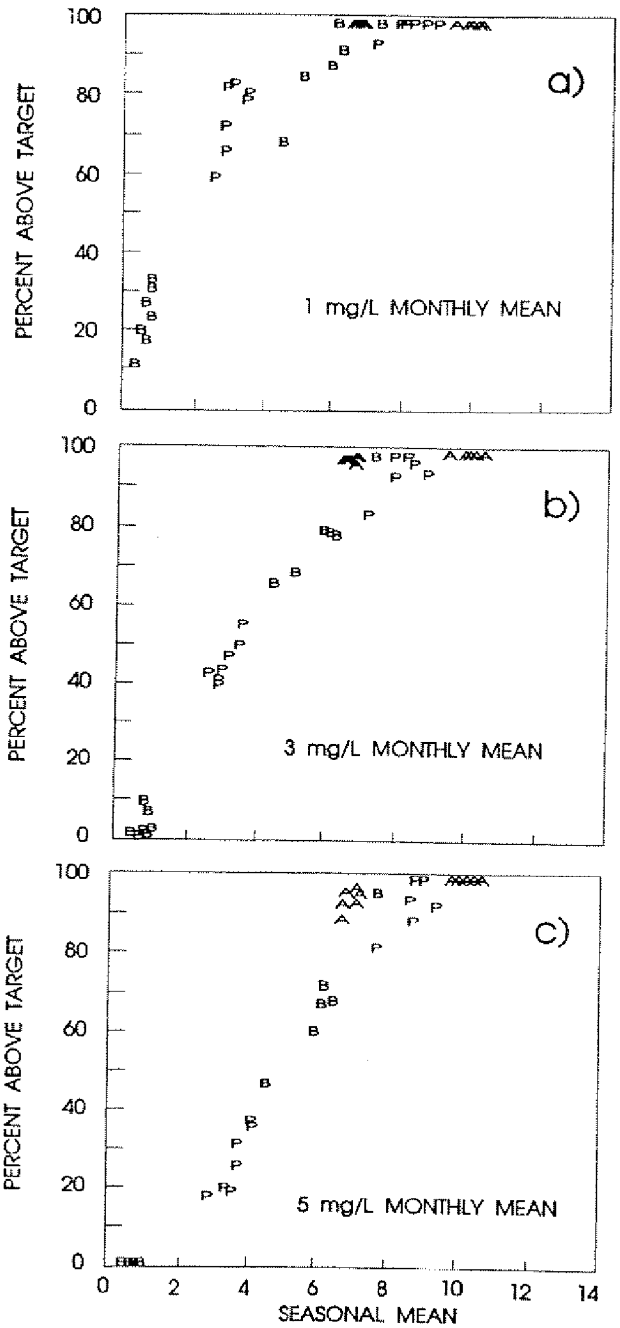

Figure IV-8. Examples of the empirical relationship between observed annual seasonal (spring and summer only) mean dissolved oxygen concentration (mg/L) and the percent of those observations above the restoration target concentrations for Chesapeake Bay Program segment CB4, for the years 1984 through 1990. Spring includes the months of March, April, and May; summer includes June through September. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A = above pycnocline, P = region of the pycnocline, and B = below pycnocline.
a. 1 mg/L at any time
b. 3 mg/L (without duration or return constraints)
c. 5 mg/L monthly average

In Figure IV-8, the percentage of observations above the target concentration is plotted versus the seasonal mean. The seasonal mean DO concentration projected by the time-variable model for each cell is related, in part, to whether the cell is above, in, or below the pycnocline. Similarly, in the analysis of the Monitoring Program data, the seasonal mean DO concentration and the number of measurements above each target concentration were calculated separately for each depth layer in each segment. The points in the plot approximate a curve, which in some segments approaches a straight line. Equations describing the curves for each target concentration were obtained for each segment by regression analysis using arcsine-transformed data. The equations and plots for all mainstem Chesapeake Bay Program and time-variable model segments, as well as the details of this analysis, are given in Appendix B.

The seasonal mean concentration which will achieve the goal can be derived from the regression equations. Conversely, given the mean DO concentration for a season in a particular segment, the percentage of observations that will meet the targets can be estimated. Table IV-5 shows the seasonal mean DO

Table IV-5. Seasonal mean DO concentrations (mg/L) required in Chesapeake Bay Program segment CB4 to achieve the indicated percentage of observations meeting or exceeding the specified target concentration. The 5 mg/L instantaneous target concentration for anadromous fish spawning and nursery habitats is not applicable to this segment.

Percent of observations ≥ target	Target concentration		
	1 mg/L[1]	3 mg/L[2]	5 mg/L[3]
100	9.1	11.2	17.2
99	6.7	8.4	9.1
90	4.5	6.1	7.4
80	3.6	5.1	6.4
70	2.9	4.4	5.7
60	2.4	3.8	5.1
50	1.9	3.3	4.5
40	1.4	2.8	4.0
30	1.0	2.3	3.5
20	0.5	1.8	2.9
10	0.0	1.3	2.2

[1] instantaneous
[2] instantaneous (target concentration permits DO ≥1 mg/L and ≤3 mg/L for <12 hours.)
[3] monthly mean

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concentrations required to achieve 10, 20, 30,. . ., 90, 99, and 100% of the goal in example segment CB4. The unreasonably large increase in mean DO required to go from 99% to 100% attainment is notable in this example and is similarly large for other segments as well. The 100% level requires DO concentrations exceeding typical saturation levels in summer. The asymptotic nature of this relationship dictates that for physical reasons the target concentrations cannot be achieved 100% of the time. For this reason, and because of both variability and statistical uncertainty in the analysis, a somewhat lower percentage should be deemed successful in achieving the restoratio goal and providing living resources with maximun protection from harmful effects of low DO condition

Knowing the seasonal mean DO concentration for a area in the Bay, therefore, permits a good estimate c what proportion of actual DO observations are likel to meet, or fail to meet, each of the target concentr tions. For example, there was good agreemer between actual and predicted percent achievement i example segment CB4 (Table IV-6). In regions whe the range of DO values in the Monitoring Progra

Table IV-6. Summer mean DO concentrations above the pycnocline (layer A), in the region of the pycnocline (layer P), and below the pycnoc (layer B) in Chesapeake Bay Program segment CB4, 1984 through 1990, comparing observed and predicted percentages of observations ≥ target concentrations. The 5 mg/L instantaneous target concentration for anadromous fish spawning and nursery habitats is not applicabl this segment; the 5 mg/L monthly mean target concentration is not applicable below the pycnocline.

			Observed Percentage			Predicted Percentage		
		Observed	Target Concentration			Target Concentration		
Year	Layer	Mean	1 mg/L[1]	3 mg/L[2]	5 mg/L[3]	1 mg/L[1]	3mg/L[2]	5 mg/L[3]
1984	A	6.5	99.6	97.6	88.9	98.7	92.7	81.2
	P	2.6	60.4	43.4	-	64.6	35.4	-
	B	0.7	18.3	9.8	-	24.3	3.1	-
1985	A	6.5	100.0	98.1	92.5	98.7	92.8	81.3
	P	2.9	83.1	44.4	-	70.6	42.5	-
	B	0.8	34.0	0.9	-	27.0	4.3	-
1986	A	6.6	99.5	97.5	95.6	98.9	93.3	82.2
	P	2.9	73.6	40.1	-	69.4	41.1	-
	B	0.9	31.7	2.4	-	28.0	4.9	-
1987	A	6.9	100.0	99.5	97.1	99.2	94.7	85.3
	P	3.2	84.2	47.8	-	74.4	47.5	-
	B	0.6	20.7	1.0	-	21.8	2.1	-
1988	A	6.8	99.9	99.1	96.1	99.2	94.4	84.6
	P	3.6	81.6	56.1	-	79.7	54.9	-
	B	0.4	12.1	1.4	-	17.5	0.8	-
1989	A	6.8	99.6	96.2	92.8	99.1	94.3	84.4
	P	2.9	67.2	41.6	-	69.4	41.1	-
	B	0.9	24.6	7.2	-	27.4	4.8	-
1990	A	6.8	100.0	98.7	95.2	99.1	94.3	84.4
	P	3.5	80.1	50.8	-	78.7	53.4	-
	B	0.7	28.1	2.4	-	24.1	3.0	-

[1]instantaneous
[2]instantaneous (target concentration permits DO ≥ 1 mg/L and ≤ 3 mg/L for 12 hours)
[3]monthly mean

data is narrow and DO has always been above the target concentrations (as is the case in some shallow areas of the mainstem Bay, the lower mainstem Bay segments, and in the transition and tidal fresh regions of most tributaries) such a relationship cannot be established. In these cases, the goal states that DO conditions may not become worse, e.g., seasonal mean DO should not go below the lowest seasonal mean recorded in the segment which had no measurements below target levels.

Time-variable Model Scenarios and Progress Toward the Restoration Goal

The Chesapeake Bay time-variable water quality model has a major role in reevaluating the Baywide Nutrient Reduction Strategy. The model is being used to test specific sub-basin scenarios for the effect of nutrient load reductions in the surrounding Bay tributary watersheds on DO and other water quality parameters. Chesapeake Bay Program managers will compare these model-simulated DO concentrations and their spatial distributions with existing DO conditions and with the DO restoration goal.

What might "improvement" look like?

Earlier Chesapeake Bay steady-state water quality models projected that reducing basinwide inputs of nitrogen and phosphorus from point and nonpoint sources would improve summer-averaged DO levels in the mainstem Bay. Improvements of this nature are not expected to significantly change the frequency or pattern of DO fluctuations, which are largely dictated by physical factors. However, the entire distribution of water column DO concentrations is expected to rise, and the amplitude of fluctuations in concentration is expected to decrease.

A hypothetical result of nutrient load reductions might be to increase seasonal mean DO by 1.5 mg/L. How this increase might be expressed in a selected living resource habitat is illustrated in Figure IV-9a, an adaptation of one of the semicontinuous records presented earlier. Raising each of the DO observations in this time series by 1.5 mg/L (with the constraint that the new value not exceed the saturation concentration unless the original measurement did) has the effect of shifting the cumulative frequency distribution to the right and reducing the number and duration of low DO occurrences (Figure IV-9b). The four-week mean is increased from 4.7 to 6.1 mg/L, episodes below 1.0 mg/L are eliminated, and the longest period of exposure to DO <3.0 mg/L is about nine hours. Therefore, an overall increase in DO of 1.5 mg/L results in full achievement of the DO restoration goal at this site. Two Gulf Coast estuaries, one significantly more impacted by anthropogenic effects than the other, have shown an analogous pattern, where, with DO variability of the same order of magnitude, the overall DO levels were higher in the less impaired waterbody (Summers 1992).

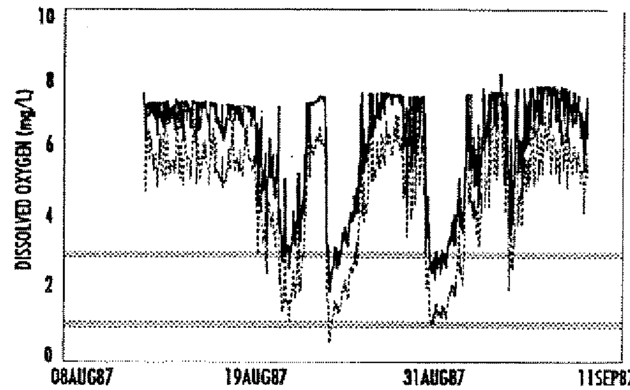

Figure IV-9a. Observed dissolved oxygen concentration (---) at Choptank River mouth (see Figure IV-1b) and hypothetical concentrations (——) representing a 1.5 mg/L overall increase in dissolved oxygen. ······ 1 and 3 mg/L reference lines.

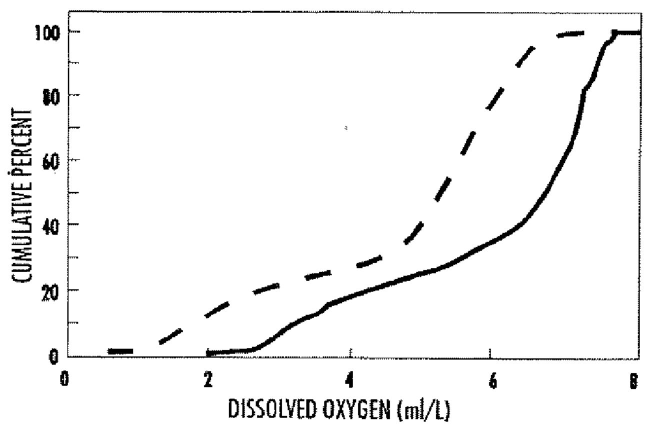

Figure IV-9b. Cumulative frequency distributions of the observed (---) and hypothetical (—) dissolved oxygen data in Figure IV-9a showing the reduced occurrence of values at the low end of the distribution.

As discussed earlier, the most reliable model projections for DO are output as seasonal means for all the model cells in each model segment. The model scenario output can be linked directly to the DO restoration goal using the same empirical relationship developed from Monitoring Program data, between seasonal means and the percent of observations which achieve, or fail to achieve, the target concentrations. Equations describing the relationship have been determined for each target concentration for each model segment (Appendix B).

Evaluating the Time-Variable Model Scenario Output

The probable percentage of observations achieving or exceeding the target concentrations for a given model scenario can be calculated from the projected model cell mean using the specific equation developed for the model segment to which the model cell belongs. The minimum seasonal mean DO concentrations that will assure achievement of each target concentration in each model segment are given in Table IV-7.

Table IV-7. Minimum seasonal mean DO concentrations (mg/L) required to achieve the DO restoration goal target concentrations based upon 99% of observations ≥ target concentrations. Values with asterisks (*) are observed seasonal means for segments where no observations were below the target concentration. The 5 mg/L instantaneous target concentration for anadromous fish spawning and nursery habitats applies only to model segments 1 and 2.

Model segment	Target concentration 1 mg/L[1]	3 mg/L[2]	5 mg/L[3]	5 mg/L[4]
1	5.1	6.8	8.5	8.0
2	6.6	8.5	9.4	9.2
3	6.6	8.3	-	9.2
4	6.4	8.2	-	8.9
5	6.0	7.4	-	8.8
6	4.0	6.4	-	7.4
7	5.2*	5.2*	-	6.4
8	5.7*	6.1	-	6.6
9	4.5*	6.2	-	7.0

[1] instantaneous
[2] instantaneous (target concentration permits DO ≥1 mg/L and ≤3 mg/L for <12 hours, so the instantaneous values are overestimates)
[3] instantaneous - applies only above the pycnocline (in anadromous fish spawning and nursery habitats)
[4] monthly mean - applies only above the pycnocline

The 3 mg/L goal component permits excursions below target concentration for periods up to 12 h, a condition suggesting seasonal means somewhat lower than those shown in Table IV-7. The seasonal means in Table IV-7 are those that should assure DO concentrations above 3 mg/L at all times. The seasonal mean required to meet the duration and frequency components of this target concentration cannot be determined from the analysis of twice-monthly Monitoring Program data. Analysis of the semicontinuous data, however, suggests that there is a relationship between seasonal mean DO and the duration as well as the frequency of low DO in particular habitats (Appendix B). At present, however, there are too few semicontinuous data sets from a wide enough variety of habitats to firmly establish such a relationship.

It is evident from Table IV-7 that there is a "controlling" target concentration for a given layer of the mainstem Bay segments, i.e. a seasonal mean that once achieved, ensures achievement of all the relevant target concentrations. In waters above the pycnocline, the controlling target concentration is 5 mg/L in segments where the anadromous fish spawning and nursery habitat target applies, and the 5 mg/L monthly mean elsewhere. Below the pycnocline, the 1 mg/L target concentration is assumed to be controlling, because we are not able to fully evaluate the duration and frequency components of the 3 mg/L target concentration at this time. Table IV-8 shows the seasonal means and controlling target concentrations required in each model segment to achieve the DO restoration goal.

Table IV-8. Minimum seasonal mean DO concentration (mg/L) required to achieve the DO restoration goal based upon 99% of observations ≥ target concentrations. Values with asterisks (*) are observed seasonal means for segments where few or no observations were below the target concentration.

Model segment	Below pycnocline	Above pycnocline
1	5.1	8.5
2	6.6	9.4
3	6.6	9.2
4	6.4	8.9
5	6.0	8.8
6	4.0	7.4
7	5.2*	6.4
8	5.7*	6.6
9	4.5*	7.0

Measuring Progress and Differentiating Between Scenario Results

The restoration goal is to provide sufficient DO by achieving, to the greatest spatial and temporal extent possible, the goal's target concentrations. For evaluating progress toward the goal and discriminating between the benefits of different nutrient load reduction scenarios, the percent achievement method described above provides a relative measure of improvement. But, a simpler means of comparing the scenarios is desirable: one which can simply depict both magnitude of difference and the geography of difference baywide. Because physical processes can inhibit full achievement of the goal, and because of uncertainties in the analysis, an interpretive scheme to evaluate goal achievement and habitat suitability was adopted.

Habitat is defined as "suitable" when the percentage achievement is 90% or greater, "marginal" if it is between 50 and 90%, and "unsuitable" if it achieves the target less than 50% of the time. Suitable or acceptable habitat provides satisfactory conditions for survival, growth and reproduction of living resources (although not necessarily fully supportive of living resources' DO requirements). Marginal habitat provides increased opportunities for benthic colonization and forage feeding. Unsuitable habitat is inhospitable to all but the most tolerant of living resources.

For each scenario, individual model cells are evaluated directly and grouped within these specific ranges. The cells are aggregated and expressed as volumes of water or areas of bottom habitat that meet or exceed the DO target concentrations. Model segments can then be mapped to show where and how much improvement or degradation is projected by each scenario.

Similarly, model cells and segments within the projected achievement category can be associated with and reported for particular existing or potential living resource habitats. The model output from the various scenarios can then be judged in terms of the specific gain or loss of critical living resource habitats.

Conclusion

The habitat requirements of representative Chesapeake Bay living resources have been synthesized to construct a DO restoration goal intended to assure the protection of most of the Bay's living resources. A method has been developed for using Chesapeake Bay Monitoring Program data to evaluate current and model-simulated future conditions of the Bay with respect to the DO restoration goal. With these methods, Bay Program managers can assess and map progress toward achievement of this goal in Chesapeake Bay on a local, regional or baywide basis. As a result of this analysis, DO concentrations projected by the model for proposed nutrient load reduction scenarios can be compared directly to the DO restoration goal.

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APPENDIX A
EFFECTS OF LOW DISSOLVED OXYGEN ON CHESAPEAKE BAY TARGET SPECIES

Tabulated from chapters in
Habitat Requirements for Chesapeake Bay Living Resources, 1991 Revised Edition,
and other sources

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References

TARGET SPECIES

BLUE CRAB
Callinectes sapidus

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
MORTALITY						
Juvenile	anoxic	20/30	10	<1 day	LT50	Stickle *et al.* 1989
Juvenile (28-54 mm)	4.6	30	10	7 days	LC50	65% saturation (Stickle *et al.* 1989)
Juvenile (28-54 mm)	5.7	30	10	28 days	LC50	79% saturation (Stickle *et al.* 1989)
Adult	<0.5	32		2 hours	Lethal	Lowery and Tate 1986
Adult	<0.5	25		4.3 hours	Lethal	Lowery and Tate 1986
Adult	0.14	24-26		13 hours	LC50	Carpenter and Cargo 1957
Adult	0.63	24-26		24 hours	LC50	Carpenter and Cargo 1957
Adult	0.3	28-30		6 hours	LC50	Carpenter and Cargo 1957
Adult	0.63	28-30		15 hours	LC50	Carpenter and Cargo 1957
Adult	0.45	30		14 hours	Lethal	100% mort. (Carpenter and Cargo 1957)
TOLERATE						
Adult	1.0	28-30		21-24 hours	Mortality	5-20% mort. (Carpenter and Cargo 1957)
Adult	2.8-3.2	21-23	~15	23-25 days	Mortality	<20% mort. of adult males at 35.5 to 39% saturation (deFur *et al.* 1990)
Adult	2.8-3.2	21-23	~15	7 days	Survival	No mort.; adult males (deFur *et al.* 1990)
FIELD OBSERVATIONS						
Adult	0	25		12 hours	Lethal	100% mort. (Carpenter and Cargo 1957)
Adult	0.1-3.0			1-3 days	Lethal	Catch was much reduced and crabs in pots dead or nearly so (Abbe 1983)
Adult	0.7-1.6	26		24 hours	Mortality	10% mort. (Carpenter and Cargo 1957)
Adult	0.7-1.6	26		27 hours	Mortality	15% mort. (Carpenter and Cargo 1957)
Adult	<2.0				Lethal	≥50% dead in pots below 7m (Carpenter and Cargo 1957)
Adult	~2.5	~30			Lethal	32-36% saturation lethal to animals in pots (Carpenter and Cargo 1957)
Adult	3.6	27		27 hours	Mortality	3% mort. (Carpenter and Cargo 1957)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
HARD CLAM						
Mercenaria mercenaria						
MORTALITY						
Larva	0.2	25		14 days	Mortality	100% mort. (Morrison 1971)
Larva	0.9	25		14 days	Mortality	0% mort. (Morrison 1971)
Adult (?) (31-38 mm)	0.9	19		21 days	Mortality	0% mort. (Savage 1976)
TOLERATE						
Larva	0.9-2.4	25			Growth	Reduced growth (Morrison 1971)
Juvenile	0.5				Development	Minimum for normal development (Morrison 1971)
Adult	4.2				Growth	Growth rate reduced below 4.2 mg/L (Morrison 1971)
Adult	<1.0				Behavior	Activity maintained (Savage 1976)
Adult (?) (31-38 mm)	0.9-1.8	17-24			Behavior	Reduced burrowing rate (Savage 1976)
Adult	5.0				Respiration	Reduced oxygen consumption below 5.0 mg/L (Hamwi 1968; 1969)
	<5.0				Stress	DO of <5.0 mg/L clearly represents stress to hard clams (Roegner and Mann 1991)
SUITABLE						
Adult (?) (31-38 mm)	5.7	19-24			Behavior	Maximum burrowing rate (Savage 1976)
Adult	>5.0				Respiration	Resp. most efficient (Hamwi 1968; 1969)
SOFTSHELL CLAM						
Mya arenaria						
MORTALITY						
Adult					Survival	Can survive near-anoxic conditions for up to 7 days (McCarthy 1969)
Adult	0.2	10		21 days	LC50	Without sulfide (Theede *et al.* 1969; Theede 1973)
Adult	0.2	10		17 days	LC50	With sulfide (Theede *et al.* 1969; Theede 1973)
Adult	0	"Very low"		"weeks"	Survival	Collip 1921

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
Adult	0	14		~8 days	Survival	Collip 1921
Adult	0	31		~1 day	Survival	Collip 1921
EASTERN OYSTER *Crassostrea virginica*						
MORTALITY						
Larva (82 µm shell length)	anoxia	22.0	12	11 hours	Lethal	Median mort. time (MMT); the time required to reach a 50% mortality (Widdows *et al.* 1989)
Juvenile (Spat)	anoxia	22.0	12	150 hours	Lethal	Median mort. time (Widdows *et al.* 1989)
Adult	0.9			96 hours	LC50	pers. comm: W. Stickle,Louisiana State University (derived from data reported in Stickle *et al.* 1989)
Adult	<1.0			5 days	Survival	Sparks *et al.* 1958
Adult (8.5 cm)	0	14-23		6-18 days	Lethal	Lund 1957
Adult	0	27-31		7 days	Lethal	Lund 1957
Adult	0	10	10-30	28 days	Mortality	Mort. <50% (Stickle *et al.* 1989)
Adult (30-50 mm)	0.8-1.5	20	10-30	28 days	LC50	Stickle *et al.* 1989
Adult (30-50 mm)	2.8-5.0	30	10-30	28 days	LC50	Stickle *et al.* 1989
Adult (30-50 mm)	anoxia	10	10-30	>28 days	LT50	Days of exposure to anoxia causing 50% mortality (Stickle *et al.* 1989)
Adult (30-50 mm)	anoxia	20	10-30	18-20 days	LT50	Stickle *et al.* 1989
Adult (30-50 mm)	anoxia	30	10-30	3-8 days	LT50	Stickle *et al.* 1989
TOLERATE						
Larva	<1.0			1 hour	Behavior	Larvae avoid areas of low DO <1 mg/L by swimming upward (Kennedy 1991)
Larva	0.5			12 hours	Behavior	Swimming rates not affected (Kennedy 1991)
Adult	30 mm Hg	20	28			Oxygen regulator down to critical oxygen tension of 30mm Hg. Below this level becomes an oxygen conformer (Shumway 1982)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
BAY ANCHOVY *Anchoa mitchilli*						
MORTALITY						
Egg (12 h post fertilization)	2.8	26.5	15-18	12 hours	LC50	Chesney and Houde 1989
Larva (12-24 h old yolk-sac)	1.6	26.5	15-18	12 hours	LC50	Chesney and Houde 1989
Larva	1.0			24 hours	Mean survival	0.025 (pers. comm: D. Breitburg, Benedict Estuarine Research Laboratory
Larva	3.1			24 hours	Mean survival	0.77 (pers. comm: D. Breitburg, Benedict Estuarine Research Laboratory)
Adult	1.9			96 hours	LC50	pers. comm: E. Houde, Chesapeake Biological Laboratory
TOLERATE						
Egg	3.0	26.5	15-18	12 hours	Hatchable	Hatchability declined significantly below 3.0 mg/L (Chesney and Houde 1989)
Larva	<2.5	26.5	15-18	12 hours	Survival	Survival of newly hatched larvae declined below 2.5 mg/L (Chesney and Houde 1989)
	<3.0				Limiting	DO <3.0 mg/L probably limits the viability and productivity of bay anchovy in Chesapeake Bay (Houde and Zastrow 1991)
MENHADEN *Brevoortia tyrannus*						
MORTALITY						
Juvenile	0.4	28	6.9		Lethal	Mean lethal concentration of oxygen was independent of the rate of reduction (Burton *et al.* 1980)
Juvenile	1.0	28	6.9	2 hours	LC5	Burton *et al.* 1980
Juvenile	1.3	28	6.9	24 hours	LC5	Burton *et al.* 1980
Juvenile	1.6	28	6.9	96 hours	LC5	Burton *et al.* 1980
Juvenile	0.7	28	6.9	2 hours	LC50	Burton *et al.* 1980
Juvenile	0.9	28	6.9	24 hours	LC50	Burton *et al.* 1980
Juvenile	1.0	28	6.9	96 hours	LC50	Burton *et al.* 1980

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
SPOT						
Leiostomus xanthurus						
MORTALITY						
Juvenile	0.6	28	6.9	1 hour	LC5	Burton *et al.* 1980
Juvenile	0.8	28	6.9	24 hours	LC5	Burton *et al.* 1980
Juvenile	0.8	28	6.9	96 hours	LC5	Burton *et al.* 1980
Juvenile	0.5	28	6.9	1 hour	LC50	Burton *et al.* 1980
Juvenile	0.7	28	6.9	24 hours	LC50	Burton *et al.* 1980
Juvenile	0.7	28	6.9	96 hours	LC50	Burton *et al.* 1980
Juvenile	0.4 mg O_2/L				LD50	Thornton 1975
FIELD OBSERVATION						
Juvenile	0.4	27	14		Minimum	Rothschild 1990
Juvenile	1.3				Minimum	Ogren and Brusher 1977
Adult	0.4	27	14		Minimum	Rothschild 1990
Juvenile	>4.0	5-30	0-Seawater		Preferred	Rothschild 1990
Juvenile	>5.0				Preferred	Ogren and Brusher 1977
Adult	>4.0	5-30	0-Seawater		Preferred	Most abundant where DO >4.0 mg/L (Rothschild 1990; Chao and Musick 1977; Markle 1976)
YELLOW PERCH						
Perca flavescens						
MORTALITY						
Larva	0.8	23	Fresh		Lethal	Petit 1973
Adult	1.5	summer	Fresh		Lethal	Thorpe 1977
Adult	0.2	winter	Fresh		Lethal	Thorpe 1977
TOLERATE						
Juvenile	<2.0	20				Growth significantly reduced (Carlson *et al.* 1980)
Juvenile	7.0					Minimum for normal respiration (Thorpe 1977)
YOY	0.8	15				Not lethal (Petit 1973)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
SUITABLE						
Egg	>5.0				Minimum	Jones *et al.* 1988
Larva	>5.0				Minimum	Jones *et al.* 1988
Juvenile	>5.0				Minimum	Jones *et al.* 1988
Juvenile	>3.5	20			Growth	Growth not affected (Carlson *et al.* 1980)
Adult	>5.0				Minimum	Jones *et al.* 1988
All	5.0				Minimum	A DO of 5 mg/L is viewed as the lowest average concentration that sustains normal development and activity (Piavis 1991)
WHITE PERCH *Morone americana*						
MORTALITY						
Juvenile	0.5-1.0	7-28	Fresh	19 hours	Mortality	40% mortality (Dorfman and Westman 1970)
TOLERATE						
Adult	3.2	8-21	2.5-12.5		Behavior	Avoid waters less than 35% saturation at 8-21°C (Meldrim *et al.* 1974)
SUITABLE						
Egg	≥5.0					5.0 or more minimum recommended for all life stages (Jones *et al.* 1988)
Larva	≥5.0					Jones *et al.* 1988
Juvenile	≥5.0					Jones *et al.* 1988
Adult	≥5.0					Jones *et al.* 1988
FIELD OBSERVATIONS						
	6.0					Concentrate in areas of at least 6 mg/L (Rothschild 1990)

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Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
STRIPED BASS *Morone saxatilis*						
MORTALITY						
Egg	<4.0	18			Mortality	Caused deformities and reduced hatch Turner and Farley 1971)
Larva	2.4	18			Lethal	yolk-sack larva (Rogers *et al.* 1980)
Post larva (28 day)	2.3			96 hours	LC50	preliminary data subject to planned replication (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett)
Juvenile (78 day)	1.6			96 hours	LC50	preliminary data subject to planned replication (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett)
Juvenile	<3.0				Mortality	Chittenden 1972; Krouse 1968
TOLERATE						
Egg	3.0	19				Striped bass eggs could hatch (Harrell and Bayless 1981)
Egg	4.9-5.0	18			Minimum	Minimum levels for normal hatching (O'Malley and Boone 1972)
Juvenile	3.6				Minimum	Required for survival (Bowker 1969)
Juvenile	3.8-4.0	18			Behavior	Avoidance at 41-44% saturation (Meldrim *et al.* 1974)
Juvenile	<3.5 (~59 torr PO_2)			30 days	Growth	Fish grew to only 127.8% of their initial body weight (Dorfman and Westman 1970: reported in Cech *et al.* 1984)
Juvenile	>7.3 (~123 torr PO_2)			30 days	Growth	Fish grew to 154.2% of their initial body weight (Dorfman and Westman 1970: reported in Cech *et al.* 1984)
Adult	3.0	16-19			Sublethal	Physiologically Stressed (Chittenden 1972; Coutant 1985)
Adult	2.0				Avoidance	Coutant 1985
All	<3.4				Behavior	Striped bass of all ages avoid waters with DO <3-4 mg/L (Cheek *et al.* 1985; Rothschild 1990)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
SUITABLE						
Egg	>5.0	18			Suitable	Turner and Farley 1971
Larva & Juvenile	5-6				Suitable	Bogdanov *et al.* 1967
Larva	≥5.0	18				ASMFC 1987
Juvenile	-				Behavior	Low DO reduces appetite (Hoff *et al.* 1966)
Juvenile (YOY)	≥5.0				Suitable	Krouse 1968; Jones *et al.* 1988 ASMFC 1987
Adult	≥5.0				Suitable	Jones *et al.* 1988
FIELD OBSERVATIONS						
	≥6.0				Presence	Most striped bass caught in 1988-89 intensive trawl survey in areas ≥6.0 mg/L (Rothschild 1990)
ALEWIFE *Alosa pseudoharengus*						
MORTALITY						
Adult	2.0-3.0			16 hours		33% mortality (Dorfman and Westman 1970)
TOLERATE						
Adult	0.5			5 minutes	Survival	Adults could survive exposure to DO concentrations as low as 0.5 mg/L for up to 5 minutes if access to an area of DO concentrations >3 mg/L was available (Dorfman and Westman 1970)
Adult	<2.0				Behavior	Test fish moved toward the surface of the test chamber (Dorfman and Westman 1970)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
SUITABLE						
Egg	5.0				Minimum	Jones *et al.* 1988
Larva	5.0				Minimum	Jones *et al.* 1988
Juvenile (YOY)	3.6				Minimum	Jones *et al.* 1988
Adult	3.6				Minimum	Jones *et al.* 1988
FIELD OBSERVATIONS						
Juvenile (YOY)	2.4-10.0					Selected areas when DO ranged from 2.4 to 10.0; Cape Fear, NC (Davis and Cheek 1966)
BLUEBACK HERRING *Alosa aestivalis*						
MORTALITY						
Juvenile	2.0-3.0			16 hours	Mortality	33% mortality (Dorfman and Westman 1970)
Juvenile	low				Behavior	Unable to detect and avoid waters with low DO concentrations (Dorfman and Westman 1970)
SUITABLE						
Egg	5.0				Minimum	Jones *et al.* 1988
Larva	5.0				Minimum	Jones *et al.* 1988
Juvenile (YOY)	3.6				Minimum	Jones *et al.* 1988
Adult	5.0				Minimum	Jones *et al.* 1988
FIELD OBSERVATIONS						
Juvenile	<3.6	27.6			Mortality	Mass mortalities occurred in lower Connecticut River during summer (Moss *et al.* 1976)
Juvenile	2.4-10.0				Presence	Juveniles collected in areas with this DO range; Cape Fear, NC (Davis and Cheek 1966)
Adult	6.0				Minimum	Adults never captured at sampling stations where DO <6mg/L; Cooper and Santee Rivers, SC (Christie *et al.* 1981)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
AMERICAN SHAD *Alosa sapidissima*						
MORTALITY						
Egg	1.0				Lethal	100% mortality (Bradford *et al.* 1968)
Egg	2.0-2.5				LD50	Connecticut River shad eggs (Bradford et al. 1968)
Egg	3.5				LD50	Columbia River shad eggs (Bradford *et al.* 1968)
Juvenile	<2.0				Lethal	Miller *et al.* 1982
Juvenile	0.6				Lethal	100% mortality (Chittenden 1969, 1973)
Juvenile	<2.0				Mortality	Mortality increased (Chittenden 1969, 1973)
Juvenile	2.5-3.5				Behavior	Juvenile shad equilibrium lost (Chittenden 1969, 1973)
Juvenile	0.5	17.8		5 minutes	Survival	Could survive brief (5 min) exposures to DO concentrations as low as 0.5 mg/L (at 17.8°C) If DO levels >3mg/L were readily available to the test organisms. Juveniles apparently could not detect and quickly avoid the low DO levels (Dorfman and Westman 1970)
Adult	<2.0				Lethal	Miller *et al.* 1982
TOLERATE						
Egg	4.0				Minimum	Minimum required for good hatch with high % of normal larvae (Bradford *et al.* 1968)
Juvenile/Adult	5.0				Minimum	DO <5.0 considered sublethal (Miller *et al.* 1982)
Juvenile	<4.0					Respiratory movements increased (Tagatz 1961)
Juvenile	2-4			96 hours	Survival	No mortality (Tagatz 1961)
Juvenile/Adult	4.0				Minimum	Minimum in spawning areas (Chittenden 1973)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
FIELD OBSERVATIONS						
Egg	<5.0				Minimum	No eggs collected in the Connecticut River (Marcy and Jacobsen 1976)
Egg	6-10				Presence	Shad eggs collected in Neuse River, NC when DO in this range (Hawkins 1979)
Juvenile/Adult	<3.0				Minimum	Blocked migrations (Miller *et al.* 1982)
Juvenile/Adult	4.0-5.0				Minimum	Minimum for migrating shad; St. John River, New Brunswick (Jessop 1975)
Juvenile	4.0-5.0				Presence	Collected apparently healthy juveniles; Hudson River, NY (Burdick 1954)
HICKORY SHAD *Alosa mediocris*						
FIELD OBSERVATIONS						
Egg	5-10				Presence	Live eggs collected in areas of the Neuse River, NC with oxygen levels of 5 to 10 mg/L (Hawkins 1979)

OTHER VERTEBRATES

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
NAKED GOBY *Gobiosoma bosci*						
MORTALITY						
New recruits (≤17 mm TL)	0.35-0.60				Mortality	100% mort. (Breitburg 1992a)
Larva	≤0.15		19.8-20.7	1 hour	Mortality	100% mort. (Saksena and Joseph 1972)
Larva	0.35		19.8-20.7	2 hours	Mortality	100% mort. (Saksena and Joseph 1972)
Larva	0.86		19.8-20.7	4 hours	Mortality	50% mort. (Saksena and Joseph 1972)
Larva	0.35-0.86		19.8-20.7	24 hours	Mortality	100% mort; many larvae survived for several hours, but all died after 24 h (Saksena and Joseph 1972)
Larva	1.30		19.8-20.7	24 hours	TL50	Median tolerance limit; the oxygen concentration at which 50% of the larvae would be expected to die after 24 h (Saksena and Joseph 1972)
Larva	2.5			24 hours	LC50	pers. comm: E. Houde, Chesapeake Biological Laboratory

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
Larva (≤ 1 wk posthatch)	1.0			24 hours	Mean Survival	0.0 (pers. comm: D. Breitburg, Benedict Estuarine Research Laboratory)
Larva (≤ 1 wk posthatch)	3.0			24 hours	Mean Survival	0.98 (pers. comm: D. Breitburg, Benedict Estuarine Research Laboratory)
Larva (3-4 wks posthatch)	1.0			24 hours	Mean Survival	0.0 (per. comm: D. Breitburg, Benedict Estuarine Research Laboratory)
Larva (3-4 wks posthatch)	3.0			24 hours	Mean Survival	0.98 (pers. comm: D. Breitburg, Benedict Estuarine Research Laboratory)
Adult	2.2			96 hours	LC50	pers. comm: E. Houde, Chesapeake Biological Laboratory
Adult males	0.15-0.6				Behavior	Abandoned nest or shelter; equivalent to 2.0-7.6% saturation (Breitburg 1992a)
TOLERATE						
Egg	0.74			7.4 hours	Development	Embryo development time significantly slowed by repeated exposure to low DO concentrations (avg. min. DO = 0.74 mg/L; DO <1.0 mg/L maintained for 7.4 hours/day; days tailbud to hatch = 3.8 for control and 6.6 for low oxygen treatment). No significant difference in embryo mortality or mean total lengths of larvae from the first day's hatch. Normal embryos hatched from all nests regardless of oxygen treatment (Breitburg 1992a)
New recruits (≤17 mm TL), juveniles, and adults	0.75-0.95	25		7 hours	Survival	All individuals tested survived; equivalent to 9.5 - 12.1% saturation (Breitburg 1992a)
STRIPED BLENNY *Chasmodes bosquianus*						
MORTALITY						
Larva	≤0.70		19.8-20.7	1 hour	Mortality	100% mort. (Saksena and Joseph 1972)
Larva	2.50		19.8-20.7	24 hours	TL50	Median tolerance limit (Saksena and Joseph 1972)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
SKILLETFISH *Gobiesox strumosus*						
MORTALITY Larva	0.72-1.23		19.8-20.7	24 hours	TL50	Median tolerance limit estimated to lie between 0.72 and 1.23 (Saksena and Joseph 1972)
WINTER FLOUNDER *Pseudopleuronectes americanus*						
MORTALITY Embryo through hatch	1.9			96 hours	LC50	pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett
Larva	1.5			96 hours	LC50	pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett
Juvenile	1.4			96 hours	LC50	pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett
YOY	0.6	20		2-4 hours	Mortality	50% dead in 2 h, 100% dead in 4 h (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett)
TOLERATE YOY	2.2	20.6-20.8	25.5	10-11 weeks	Growth	Growth of YOY held at constant low DO (~29% saturation) was significantly reduced (< half) compared to YOY held at constant high DO (6.7 mg/L; ~ 90% saturation) (Bejda *et al.* 1992)
YOY	2.5-6.4	20.6-20.8	25.5	10-11 weeks	Growth	Growth of YOY held at diurnally fluctuating DO ranging from 2.5 to 6.4 mg/L (~ 30 to 90% saturation) was intermediate compared to YOY held at constant low (2.2 mg/L) or constant high (6.7 mg/L) DO (Bejda *et al.* 1992)
YOY	1.4	20.6-20.8	25.5	Several hours	Mortality	YOY exposed to diurnally fluctuating levels of DO (2.5 - 6.4 mg/L) suffered 60% mortality when subjected to a sudden decrease in DO down to 1.4 mg/L; whereas YOY exposed to constant low DO (2.2 mg/L) suffered 0% mortality when subjected to a sudden decrease (Bejda *et al.* 1992)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
RED DRUM *Sciaenops ocellatus*						
Larva	1.1	27		96 hours	LC50	pers. comm: D. Miller and S. Poucher, EPA ERL Narragansett)
OTHER INVERTEBRATES						
MOLLUSCS *Littorina littorea* (Marsh snail)						
Adult	0.15	10		365 h (15.2 days)	LD50	Without sulfide (Theede *et al.* 1969; Theede 1973)
Adult	0.15	10		180 h (7.5 days)	LD50	With sulfide (Theede *et al.* 1969; Theede 1973)
Macoma baltica (Baltic macoma clam)						
Adult	0	10		7 days	Mortality	4% (Thamdrup 1935)
Adult	0	10		500 h (20.8 days)	LD50	Dries and Theede 1974
Mulinia lateralis (Little surf clam)						
Juvenile (5 mm)	0	10		10.5 days	LT50	Without sulfide (Shumway and Scott 1983)
Juvenile (5 mm)	0	10		4.3 days	LT50	With sulfide (Shumway and Scott 1983)
Juvenile (5 mm)	0	20		7.5 days	LT50	Shumway and Scott 1983
Juvenile (5 mm)	0	30		2 days	LT50	Shumway and Scott 1983)
Adult (10 mm)	0	10		10 days	LT50	Without sulfide (Shumway and Scott 1983)
Adult (10 mm)	0	10		3.8 days	LT50	With sulfide (Shumway and Scott 1983)
Adult (10 mm)	0	20		2.5 days	LT50	Shumway and Scott 1983
Adult (10 mm)	0	30		1.8 days	LT50	Shumway and Scott 1983

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
POLYCHAETES *Nereis virens* (Blood worm)						
Adult	0	6-8		72 hours	Stress	ATP conc. 57% of initial value, after 72 h; energy charge (=0.77) indicates stress (Schottler 1979)
Capitella species 1	pO_2<15 mm Hg	22	28	<8 hours	Behavior	Within ~8 h, as pO_2 declined from 150 to <15 mm of Hg, all worms stopped feeding and crawling and remained quiescent. There was no mortality during the 48 h experiment (Forbes and Lopez 1990)
Capitella species 1	pO_2 ~35 mm Hg	22	28	48 hours	Growth	Within the high food treatments, a reduction in environmental pO_2 from 130 to 35 mm of Hg decreased the growth rates of worms by up to 36% per day (Forbes and Lopez 1990)
ARTHROPODS *Crangon crangon*						
Adult	0.2	10		2 hours	LC50	Without sulfide (Theede *et al.* 1969; Theede 1973)
Adult	0.2	10		2 hours	LC50	With sulfide (Theede *et al.* 1969; Theede 1973)
Adult	0	10		2 hours	LD50	Dries and Theede 1974
Adult	5% sat. (~0.4)	20	20	1.5 hours	LC50	Hagerman and Szaniawska 1986
Adult	10% sat.	20	5	1.5 hours	LC50	Hagerman and Szaniawska 1986
	10% sat.	20	10	4.5 hours	LC50	Hagerman and Szaniawska 1986
	10% sat.	20	20	6 hours	LC50	Hagerman and Szaniawska 1986
	20% sat.	20	5	70 hours	LC50	Hagerman and Szaniawska 1986
	20% sat.	20	10	150 hours	LC50	Hagerman and Szaniawska 1986
	20% sat.	20	20	150 hours	LC50	Hagerman and Szaniawska 1986
	30%/50% sat.	20	5	150 hours	LC50	Hagerman and Szaniawska 1986
	30%/50% sat.	20	10	150 hours	LC50	Hagerman and Szaniawska 1986
	30%/50% sat.	20	20	150 hours	LC50	Hagerman and Szaniawska 1986

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
Crangon septemspinosa (sand shrimp)						
Juvenile/Adult	0.5	20.5		1 hour	Mortality	100% dead or moribund (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett)
Juvenile/Adult	1.5	20	31	96 hours	LC50	preliminary data subject to planned replication (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett
Palaemonetes pugio (Grass shrimp)						
Larva	1.9			96 hours	LC50	pers. comm: W. Stickle, Louisiana State University (derived from data published in Stickle *et al.* 1989)
Juvenile/Adult	1.6			96 hours	LC50	pers. comm: W. Stickle, Louisiana State University (derived from data published in Stickle *et al.* 1989)
Palaemonetes vulgaris (grass shrimp)						
Larva	0.8			1.4 hours	LT50	preliminary data subject to planned replication (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett)
Larva	1.0			1.8 hours	LT50	preliminary data subject to planned replication (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett)
Larva	1.4			2.9 hours	LT50	preliminary data subject to planned replication (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett)
Larva	1.6			21.6 hours	LT50	preliminary data subject to planned replication (pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett)
Eurypanopeus depressus (Mud crab)						
	0.6			96 hours	LC50	pers. comm: W. Stickle, Louisiana State University (derived from data published in Stickle *et al.* 1989)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
Gammarus lacustris (Freshwater scud)						
Adult	2	14			Respiration	Ceased respiratory regulation (Walshe-Maetz 1952)
Ampeliscid amphipod						
Adult	<0.5			96 hours	LC50	pers. comm: D. Miller and S. Poucher, EPA ERL, Narragansett
Idotea baltica (Baltic isopod)						
Adult	0.2	10		6 hours	LC50	Without sulfide (Theede *et al.* 1969; Theede 1973)
Adult	0.2	10		6 hours	LC50	With sulfide (Theede *et al.* 1969; Theede 1973)
ECHINODERMS *Ophiura albida*						
Adult	0.9	13			Mortality/ Behavior	30% of 70 specimens showed O_2 deficiency posture or mortality (Westernhagen and Dethlefsen 1983)
Adult	0.9	13			Mortality/ Behavior	16% mort. of 70 specimens (Westernhagen and Dethlefsen 1983)
Adult	1.6	11-12			Mortality/ Behavior	13% of 168 specimens showed O_2 deficiency posture or mortality (Westernhagen and Dethlefsen 1983)

Species/ Life Stage	Dissolved Oxygen (mg/L)	Temp (°C)	Salinity (ppt)	Duration	Effect	Comments and References
Adult	1.6	11-12			Mortality/ Behavior	4% mort. of 168 specimens (Westernhagen and Dethlefsen 1983)
Adult	3.1-3.7	12			Mortality/ Behavior	7% of 118 specimens showed O_2 deficiency posture or mortality (Westernhagen and Dethlefsen 1983)
MESOZOOPLANKTON						
Acartia tonsa (copepod)	0.8			24 hours	LC50	pers. comm: E. Houde, Chesapeake Biological Laboratory
MACROZOOPLANKTON						
Chyrsaora quinquecirrha (Sea nettle)	0.7			96 hours	LC50	pers. comm: Ed. Houde, Chesapeake Biological Laboratory
Mnemiopsis leidyi (ctenophore)	1.0			96 hours	LC50	pers. comm: E. Houde, Chesapeake Biological Laboratory

APPENDIX B
TECHNICAL ADDENDUM

B1. Definition of Pycnocline

B2. Technical Description of Data Reduction and Analysis of Semicontinuous and Chesapeake Bay Program (CBP) Monitoring Data

B3. Plots of Percent Above Target versus Seasonal Mean DO
- a) for mainstem model segments
- b) for mainstem CBP segments

B4. Coefficients and R^2s of Regression Equation for calculating Percent Achievement
- a) for mainstem model segments
- b) for mainstem CBP segments

B5. Minimum Seasonal Mean Dissolved Oxygen Concentration required to Achieve the DO Restoration Goal.
- a) for mainstem model segments
- b) controlling concentrations for mainstem model segments
- c) for mainstem CBP segments
- d) controlling concentrations for mainstem CBP segments

B6. Steps for Determining Water Quality Status Relative to the Dissolved Oxygen Restoration Goal
- a) Calculating Percentage Achievement From Time-Variable Model Output
- b) Calculating Percentage Achievement From Monitoring Program Data

B1. Definition of Pycnocline

In a partially mixed estuary like Chesapeake Bay, water density is typically heterogeneous from surface to bottom, with fresher, less dense water from the tributaries overlying saltier, denser water from the ocean. Temperature also has an effect on density. Other things being equal, warm water is less dense than cool water. Under certain physical and climatic conditions, the water column can become stratified into two or more layers of distinctly different density. The region of the water column where the density discontinuity occurs is called the pycnocline.

Certain components of the dissolved oxygen restoration goal are applied only above-pycnocline:

> "c) monthly mean dissolved oxygen concentration of at least 5.0 mg/L throughout the above-pycnocline waters of Chesapeake Bay and its tidal tributaries; and
>
> d) dissolved oxygen concentration of at least 5.0 mg/L at all times throughout the above-pycnocline waters of anadromous fish spawning reaches, spawning rivers and nursery areas of Chesapeake Bay and its tidal tributaries...".

For the purpose of evaluating time-variable model output or Monitoring Program data with respect to these components, the regions of the water column relative to the pycnocline are defined as follows.

Chesapeake Bay Time-Variable Model Output
In the model, the water column is divided into three density regions: 0 to 6.7 m, 6.7 to 12.7 m, and greater than 12.7 m (CBP 1992). The middle portion (6.7 tc 12.7) is the region of the pycnocline. For purposes oi evaluating model output relative to the DO restoration goal, the above-pycnocline region is defined b; the upper boundary of the pycnocline and include: model cells in layers 1 through 4. The below-pycnocline region includes model cells in layers 5 througl 14.

Chesapeake Bay Monitoring Program Data
When using Monitoring Program data, if the dissolved oxygen measurement is made at a time an place where at least one pycnocline exists, then th actual depth of the uppermost pycnocline marks th boundary between above-and below-pycnoclin waters. Where no pycnocline exists, the boundary i arbitrarily set at 6.7 m, to be consistent with th model.

The current Chesapeake Bay Monitoring Progran shipboard protocol for determining the pycnoclin using specific conductivity as the substitute measur of density, is as follows:

> A computed threshold value is calculated from two times the mean change in conductivity per meter between the surface and bottom. A pycnocline exists if the threshold value is greater than 500 micromhos-/cm per meter. The upper and lower boundaries of the pycnocline are the first depth interval from the surface and the first from the bottom with a change in conductivity that exceeds the threshold value.

B2. Data Reduction and Analysis

Background

The DO restoration goal specifies target DO concentrations, some of which are applicable over the entire water column and some which are applicable only above-pycnocline. The goal also specifies the duration and frequency of reoccurrence of DO below target concentrations. Monitoring data and model projections do not have sufficient temporal resolution to evaluate conformance to these limits. Therefore, relationships had to be defined among the DO target concentrations, the real-time semicontinuous dissolved oxygen fields, the twice-monthly Chesapeake Bay Monitoring Program data, and the seasonal means projected by the time-variable model.

Using Semicontinuous Data to Characterize Dissolved Oxygen in the Environment

In-situ recording devices allow the collection of close-interval (semicontinuous) DO measurements at a single point over relatively long periods. Semicontinuous data from a number of sources were used to provide examples of real-time variability in DO in several different estuarine environments. Data demonstrating summer conditions in the York River (provided by Dr. Robert Diaz, Virginia Institute of Marine Sciences) were collected at 20-minute intervals from June 21 to October 15, 1989. A subset of the complete record was used in the time-series plot (Figure IV-1a) covering July and August only. Data from the mainstem Bay near the mouth of the Choptank River (provided by Dr. Lawrence Sanford, University of Maryland) were collected at 5-minute intervals from August 12 to September 9, 1987. The entire period was used in the time-series plot characterizing the general environment (Figure IV-1b). Data from St. Leonard Creek (provided by Dr. Robert Summers, Maryland Dept. of the Environment) were collected between April 29 and October 7, 1988. Measurements were taken at 30-minute intervals. The data used in the time-series plot (Figure IV-1c) were from July and August 1988 only.

Comparing Semicontinuous and Monitoring Program Data

In the Chesapeake Bay Monitoring Program, DO measurements are made vertically and horizontally at many points in the mainstem Bay. During the summer, when sampling is most frequent, measurements are made twice a month. To evaluate the applicability of Monitoring Program DO data in assessing status and progress with respect to the DO restoration goal, the multi-location, low frequency Monitoring Program data were compared with single-location, high frequency semicontinuous data.

The semicontinuous monitoring site near the mouth of the Choptank River mentioned above was one of four sites in the middle region of the Bay that were monitored simultaneously over the four-week period. At each location, a sensor was fixed approximately 1 meter off the bottom. Dissolved oxygen was measured at three sites at 6, 13, and 19 m, respectively. At the fourth site, one sensor measured DO near the bottom at 9 m and one near mid-depth, at 6 m. These sites were in the vicinity of several monitoring stations in Chesapeake Bay Program segment CB4 (Figure IV-5) which were visited on two monitoring cruises during the deployment of the sensors. Estimates of dissolved oxygen concentration are commonly made for a station or segment by averaging the values of the two cruises within a calendar month and reported as "monthly" averages.

Because of slight differences in the dates and times of deployment, the data from each of the sensors were equalized by using only data collected from August 13 through September 6, 1987, exactly 25 days. The time interval between measurements also differed among sensors: three sensors measured at intervals of 5 minutes, one at 12 minutes, and one at 15 minutes. To adjust for this difference, only every third measurement in the 5 minute-interval records was included, and in the 12 minute-interval record, every 5th measurement was dropped. The 15 minute-interval record was not adjusted.

The Monitoring Program stations were sampled 15 days apart within the period of the sensor deployment, on August 17-18 and on September 1-2, 1987. The length of time between the two cruises was typical for the summer sampling schedule. The Monitoring Program stations included in the comparison were the stations in segment CB4: stations CB3.3C, CB3.3E, CB3.3W (which are, indeed, in segment CB4), CB4.1C, CB4.1E, CB4.1W, CB4.2C, CB4.2E, CB4.2W, CB4.3C, CB4.3E, CB4.3W, and CB4.4.

To display the data from the two sources together (Figure IV-6), all DO profile data at all thirteen stations on both cruise dates were pooled and plotted as depth versus concentration. The mean, standard deviation, minimum and maximum of each of the five adjusted semicontinuous DO data sets were superimposed on the plot at the appropriate depth.

To compare means and other summary statistics (Table IV-4), DO data from between 5 and 7 m at the thirteen Monitoring Program stations were pooled for comparison with the 6-m semicontinuous data, data between 8 and 10 m were compared with the 9-m semicontinuous data, data between 12 and 14 m were compared with the 13-m semicontinuous data, and data between 18 and 20 m were compared with the 19-m semicontinuous data. The data were rounded to the nearest 0.1 mg/L.

Cumulative percent distributions of these depth-specific groups (Figures IV-7a,b,c,d,e) were obtained by adapting the SAS "PROC FREQ" procedure. This SAS computer programming function provides the percentage of observations at each value for any variable in a dataset.

Using Monitoring Program Data To Determine a Relationship Between Seasonal Mean DO and the Percent of Observations Above Goal

An analysis of the Monitoring Program data was performed to determine the relationship between seasonal mean DO and the percentage of observations (and, by extension, the percentage of time) above target concentrations. The analysis was performed on dissolved oxygen data collected between June 1984 through September 1990 in the Chesapeake Bay Monitoring Program. Samples are routinely collected at a Baywide network of stations, twice a month in spring and summer, once a month in fall and winter. Described simplistically, the sampling protocol for profiling dissolved oxygen at Monitoring Program stations is to measure DO at the surface and at one-meter intervals to the bottom. Water temperature, salinity, and conductivity are also measured concurrently. This protocol, however, has been executed slightly differently between data collection institutions and over time. For example, if DO doesn't change with depth, measurements may not be recorded until a depth is reached where a change in DO is detected. Also, early in the Monitoring Program, some institutions made measurements at two-m depth intervals, others at 1-m. Another problem, although much rarer, is the inequality caused by missing stations or cruises or blocks of missing data due to faulty instruments.

To equalize station profiles, missing values were estimated where possible. For each station profile, sample depths greater than 0.5 m were rounded to the nearest meter. Infrequently, this resulted in more than one measurement per depth. In that case, the average concentration was used at that depth. For any meter interval missing a value in this skeleton DO profile, DO concentration was linearly interpolated from adjacent values above and below the depth of the missing value.

Prior to rounding the depths to whole meters, each depth was assigned a layer code to indicate whether it was above (A), in the region of (P), or below (B) the pycnocline. The presence or absence of a pycnocline was checked, and if one or more existed, the depth of the upper pycnocline was used. Depths between the surface and the pycnocline were assigned to the A-layer, depths below the actual pycnocline down to 12.7 m were assigned to the P-layer, and depths below 12.7 meters were assigned to the B-layer. If a pycnocline was absent, the pycnocline was arbitrarily set at 6.7 m. The A-layer was then 0-6.7 m, the P-layer was 6.8 m to 12.7, and the B-layer was any depth greater than 12.7 m. At those stations whose total depth was near a boundary depth, i.e., stations about 7-8 or 13-14 m deep, the few observations falling in the lower layer were assigned to the layer above. The data were then grouped by layer.

An alternative choice to grouping within depth layer would have been to determine the relationship by calculating the seasonal mean DO and the percentage of observations above target for each sampling point in the Monitoring Program, then pooling these. But, because the maximum number of observations at any point was so small (2 cruises/month x 4 months = 8 observations), the percentage of observations above or below a target concentration would only be eight possible values and very sensitive to missing values. Therefore, it was decided to group data within depth layers.

Because water quality varies in different areas of the Bay, it was expected that the relationship between seasonal mean DO and the percentage of observations above goal would also vary over the Bay and, thus, the relationship should be described separately for each area. The data were therefore grouped spatially according to two different schemes: one appropriate to the spatial scheme of the time-variable model, and the other conforming to the spatial aggregation units, or "segments", usually used in analyzing or evaluating Monitoring Program data.

The CBP segmentation scheme divides the Bay and its tributaries into 45 separate areas (Figure IV-3). Segments CB1 through CB8 and segment EE3 are the areas which most closely correspond to the areas of the main Bay addressed in the current time-variable model. The modelers use a different segmentation scheme for aggregating model output: they also have nine segments, segments #1 through #9, but with somewhat different internal boundaries (Figure IV-4). To determine the relationship for these areas, then, each Monitoring Program data point was assigned its appropriate CBP and model segment designation, then grouped by segment (either CBP- or model-defined segment) and by depth layer (above, below, or in the region of the pycnocline) within segment.

The data were then further grouped within season within year. The four seasons were defined as follows: winter included January and February; spring, March through May; summer, June through September; and fall, October through December. If more than one cruise was missing within a season, the data from that layer/season/year/segment were dropped from the analysis. Because segment CB1 contains only one station, approximately 6 m deep, segments CB1 and CB2 were combined for the analysis (indicated as segment CB1-2 in the plots).

To reduce the effect of supersaturated DO conditions (often caused by undesirable excess phytoplankton), DO measurements that were above the saturation concentration were set down to the saturation concentration. Saturation concentration was calculated for each DO data point using the concurrent temperature and salinity measurements collected with each sample.

The seasonal mean was then calculated for each valid layer/season/year/segment group, as was the percentage of all observations within the group that were above the DO target concentrations: 1 mg/L, 3 mg/L, 5 mg/L, monthly mean of 5 mg/L. In the fall and winter seasons, dissolved oxygen was almost always above target concentrations, and, as expected, a strong relationship between seasonal mean and the percentage of observations above or below target was not evident. Fall and winter seasons were, therefore, dropped from the analysis. Plots of the percentages as a function of spring and summer mean DO concentrations were made for each segment for each target concentration (Appendix B3).

Regression analysis was used to obtain the equation that would describe the relationship between the percentage above target and the seasonal mean DO.

As is commonly done for percentage data, an arcsine transformation of the data was used in the analysis (SAS "PROC REG"). A quadratic model obtained the best fit, where

> r = the ratio of the number of observations above target concentration to the total number of observations,

and

> arcsine(square root of r) = A*(seasonal mean)^2 + B*(seasonal mean) + C.

Because the objective was to describe this relationship within the range of seasonal means at which DO was problematic, i.e. when DO was less than 100% above target concentrations, the data for conditions supporting 100% achievement were censored: of these "100 percent" data points, the lowest seasonal mean in each season (spring and summer) each year which had 100 percent of the observations above target was included. The others were omitted from the analysis. The regression coefficients for time-variable model and CBP segments are given in Appendix Tables B4.(a) and (b), respectively.

Using Semicontinuous Data to Explore Relationships Between Seasonal Mean DO and Duration of Low DO Events

An important component of the DO Restoration Goal is the allowable duration of excursions below 3 mg/L. Excursions between 1 and 3 mg/L must be under twelve hours and the interval between such excursions should be at least 48 hours. The semicontinuous data records provide empirical observations on the frequency and duration of low DO events in particular habitats. For example, Figure B2 shows the number and duration of events where DO fell below 3 mg/L at St. Leonard Creek. Improving conditions should lead to a reduction in the number and duration of these events. We have not yet sufficiently analyzed the return frequency component of this target concentration. Further work on measuring status and progress toward this goal component is planned as additional semicontinuous data from various habitats and water quality conditions become available.

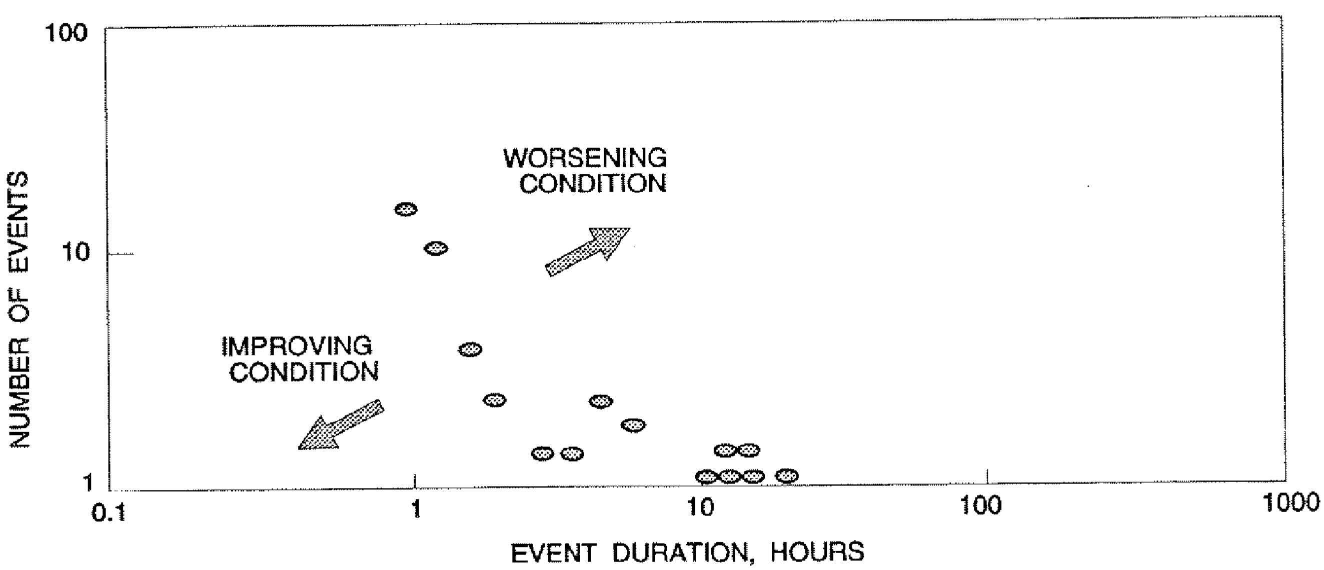

Figure B2. Number of events where DO fell below 3 mg/L at St. Leonard Creek, July and August, 1988.

B3.(a). Figures B3-a1 through B3-a9 present plots of the percent of Monitoring Program observations above target DO concentration (percent above target) versus annual seasonal mean DO concentration (seasonal mean), by mainstem model segments, for the years 1984 through 1990. Observations are grouped by segment, depth layer, season (spring and summer), and year. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline. Target DO concentrations are 1, 3, and 5 mg/L (instantaneous), and 5 mg/L monthly mean. The 5 mg/L target applies to anadromous fish spawning and nursery areas and therefore does not apply to model segments 3 through 9.

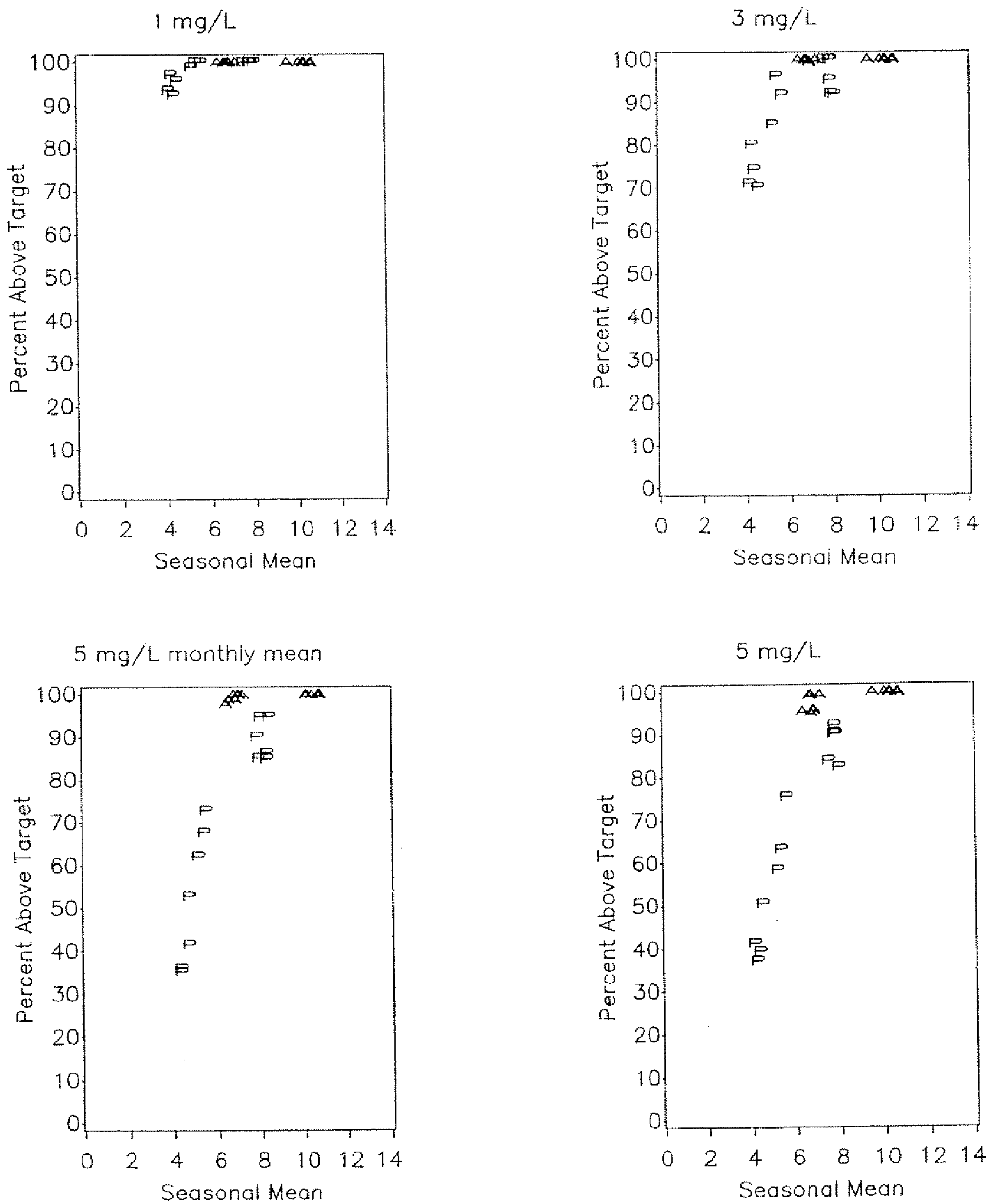

Figure B3-a1. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within model segment 1. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

B(3).b. Figures B3-b1 through B3-b8 present plots of the percent of Monitoring Program observations above target DO concentration (percent above target) versus annual seasonal mean DO concentration (seasonal mean), by mainstem CBP segments, for the years 1984 through 1990. Observations are grouped by segment, depth layer, season (spring and summer), and year. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline. Target DO concentrations are 1, 3, and 5 mg/L (instantaneous), and 5 mg/L monthly mean. The 5 mg/L target applies to anadromous fish spawning and nursery areas and therefore does not apply to CBP segments CB4 through CB8, and EE3.

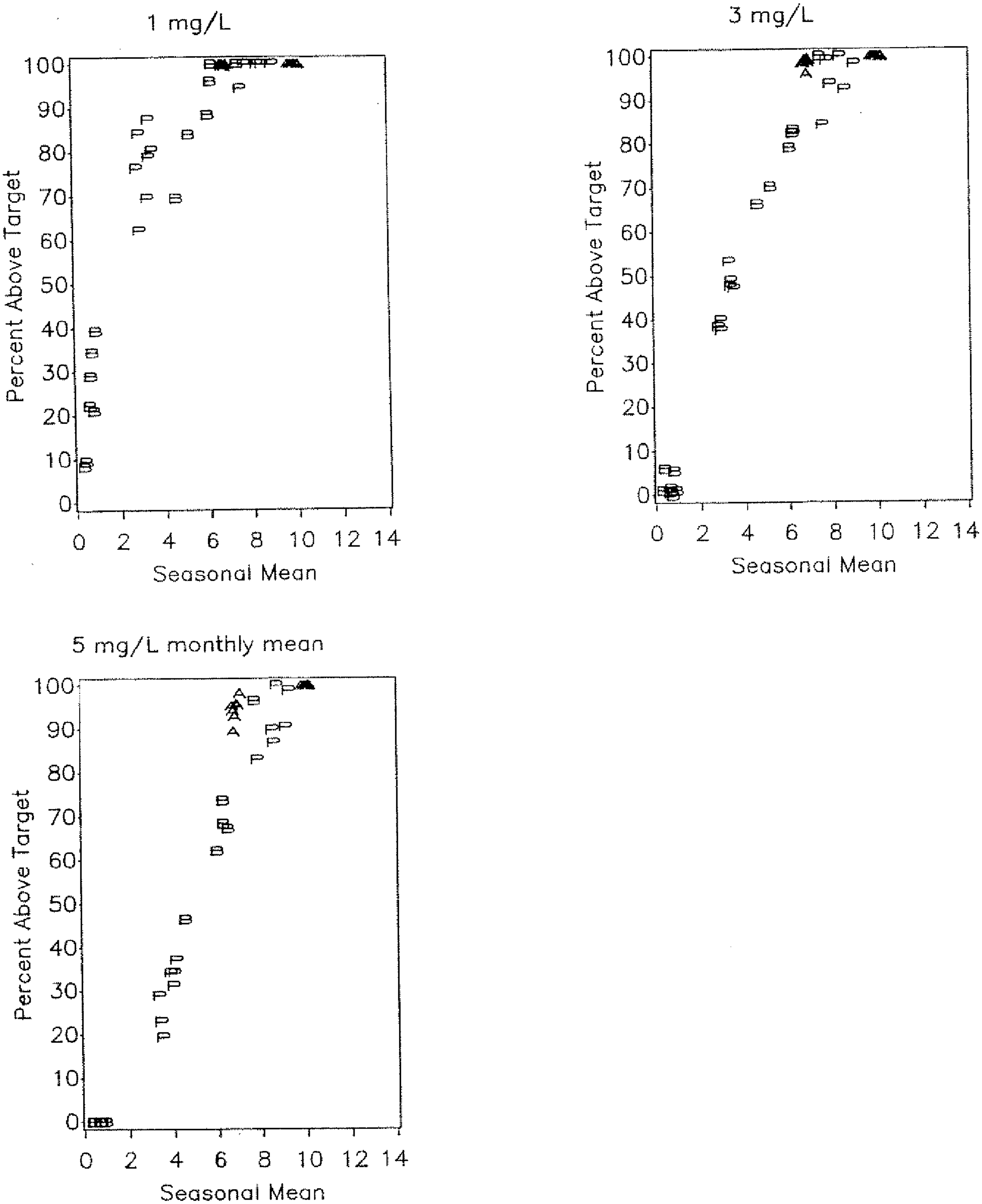

Figure B3-a3. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within model segment 3. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

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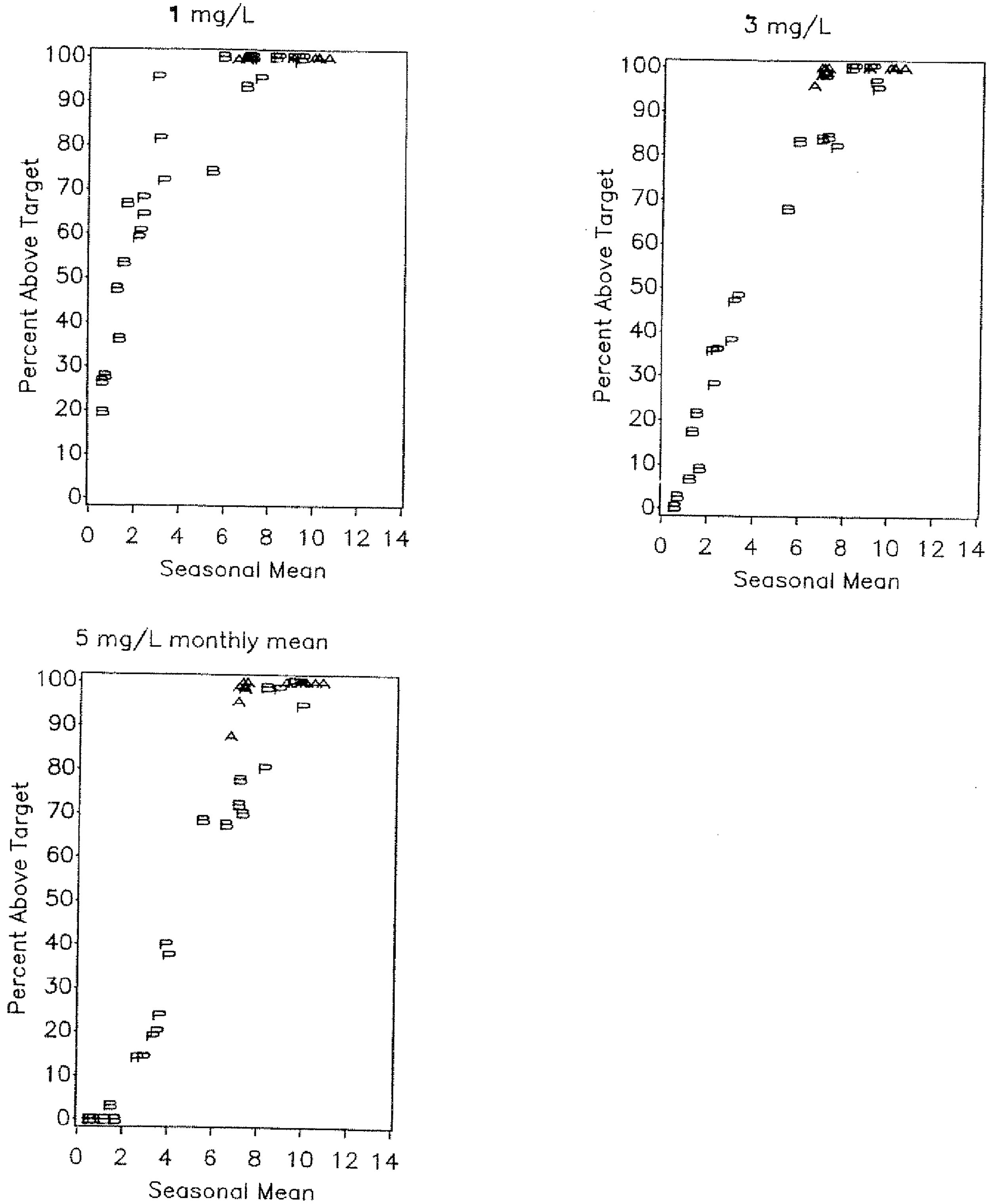

Figure B3-a4. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within model segment 4. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

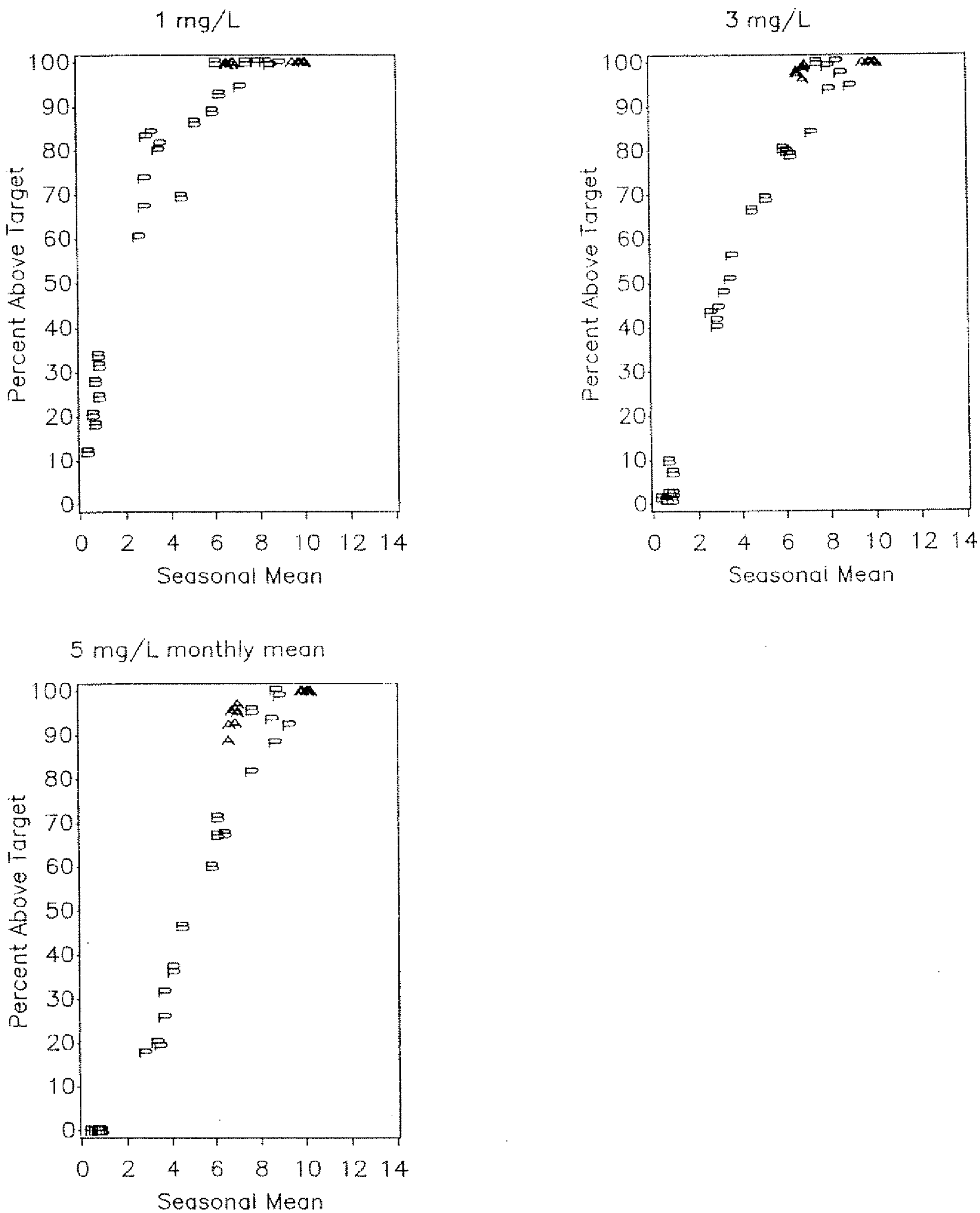

Figure B3-b3. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB4. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

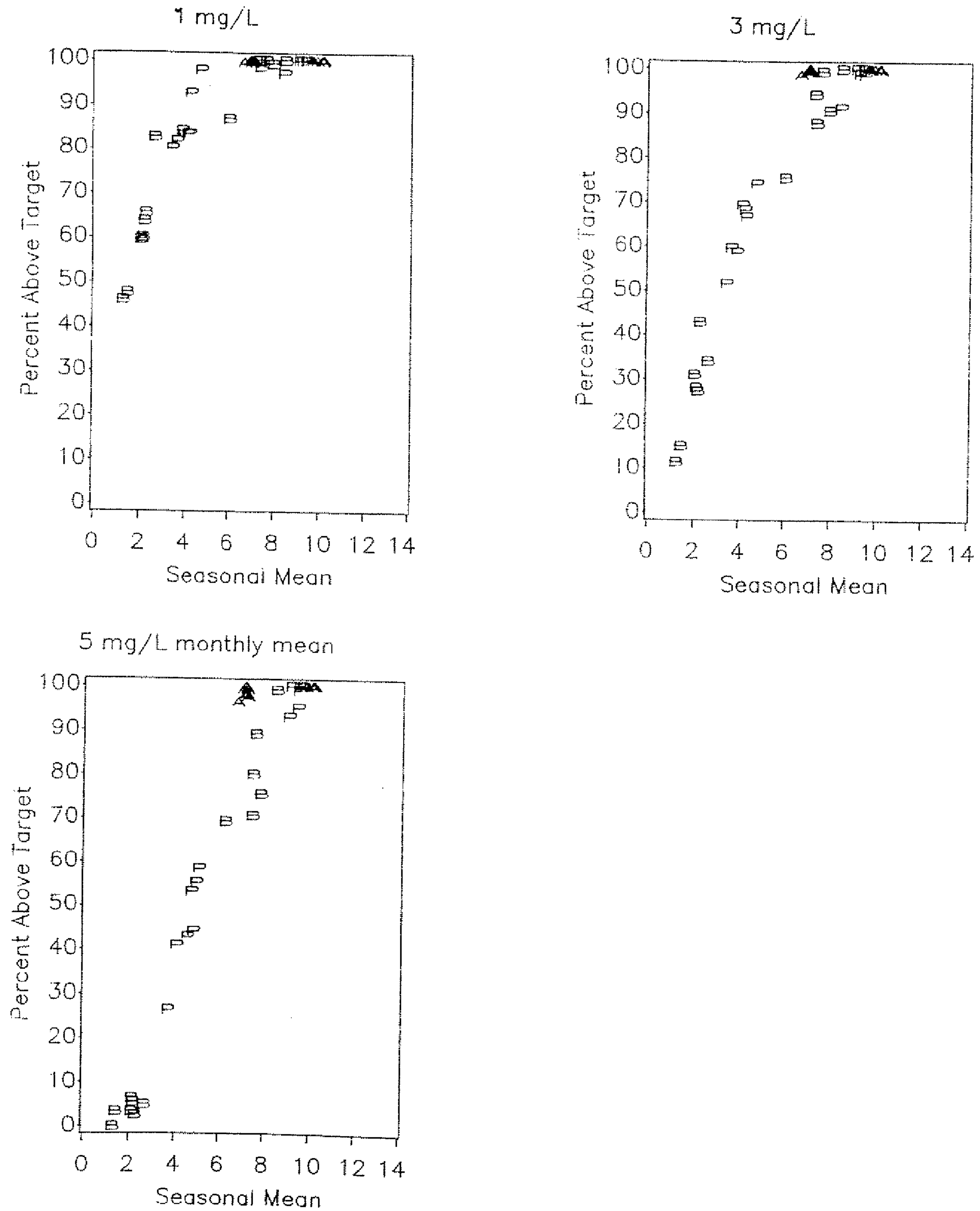

Figure B3-b4. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB5. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

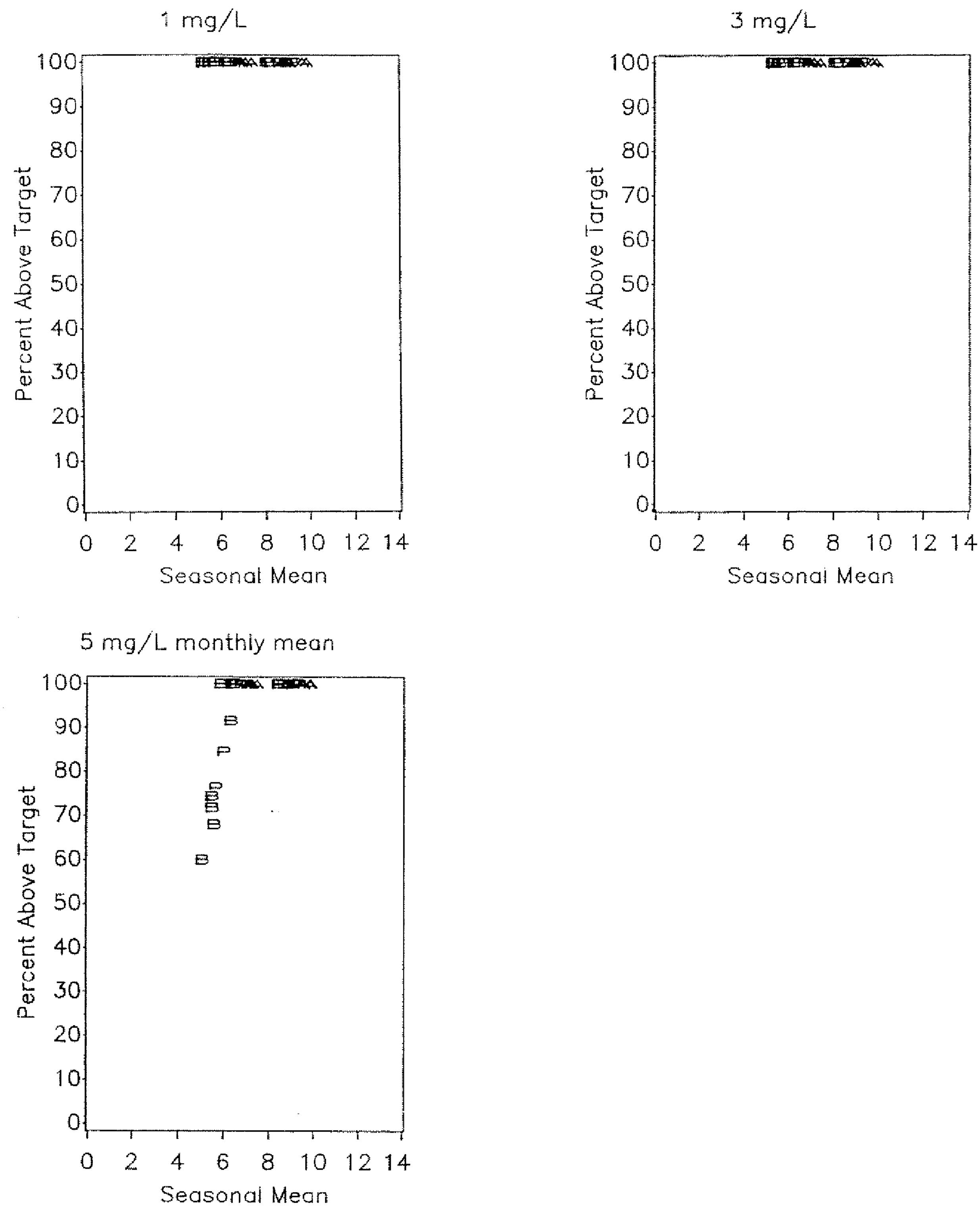

Figure B3-a7. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within model segment 7. Lett symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnoclin P=region of the pycnocline, and B=below pycnocline.

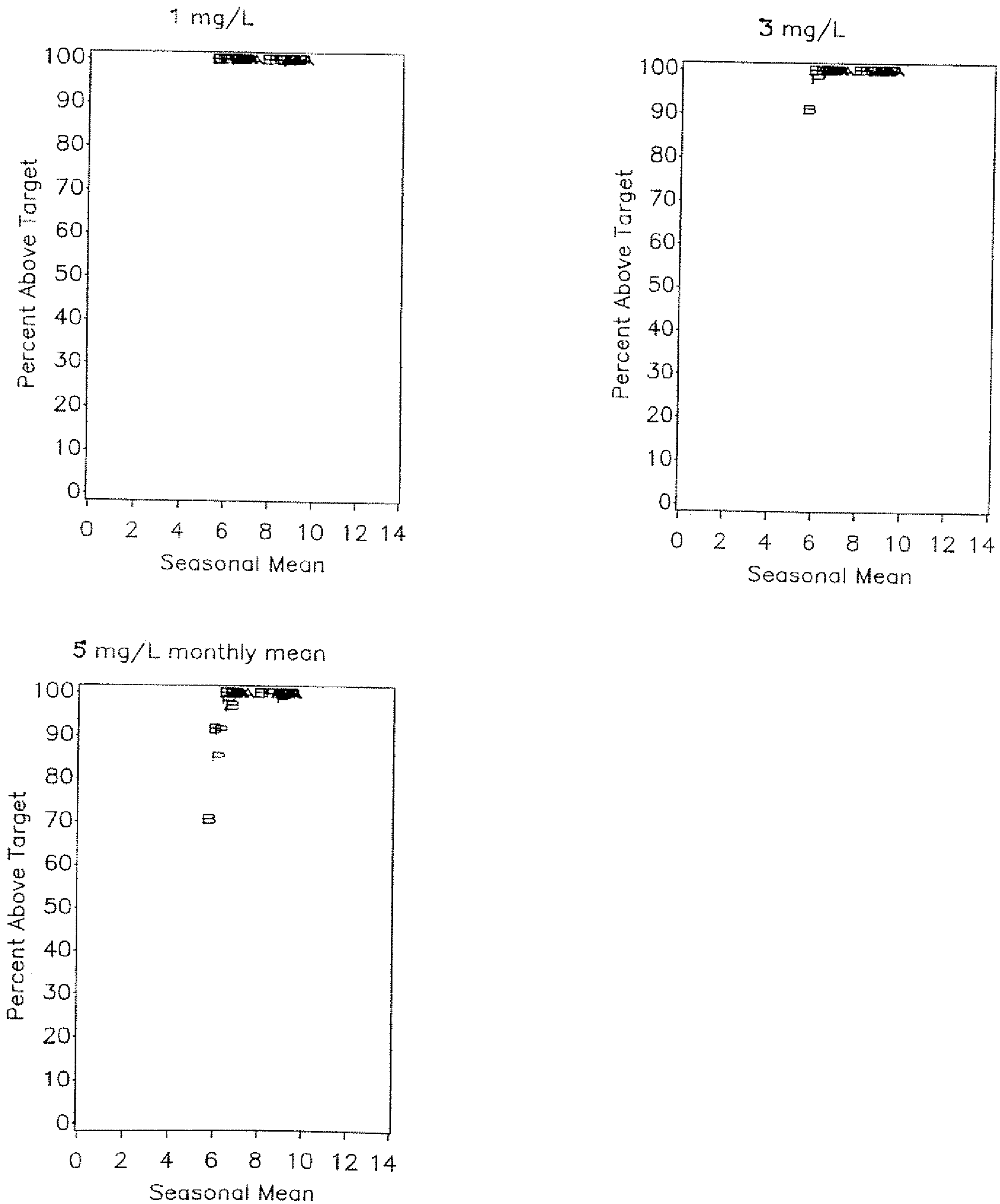

Figure B3-a8. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within model segment 8. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

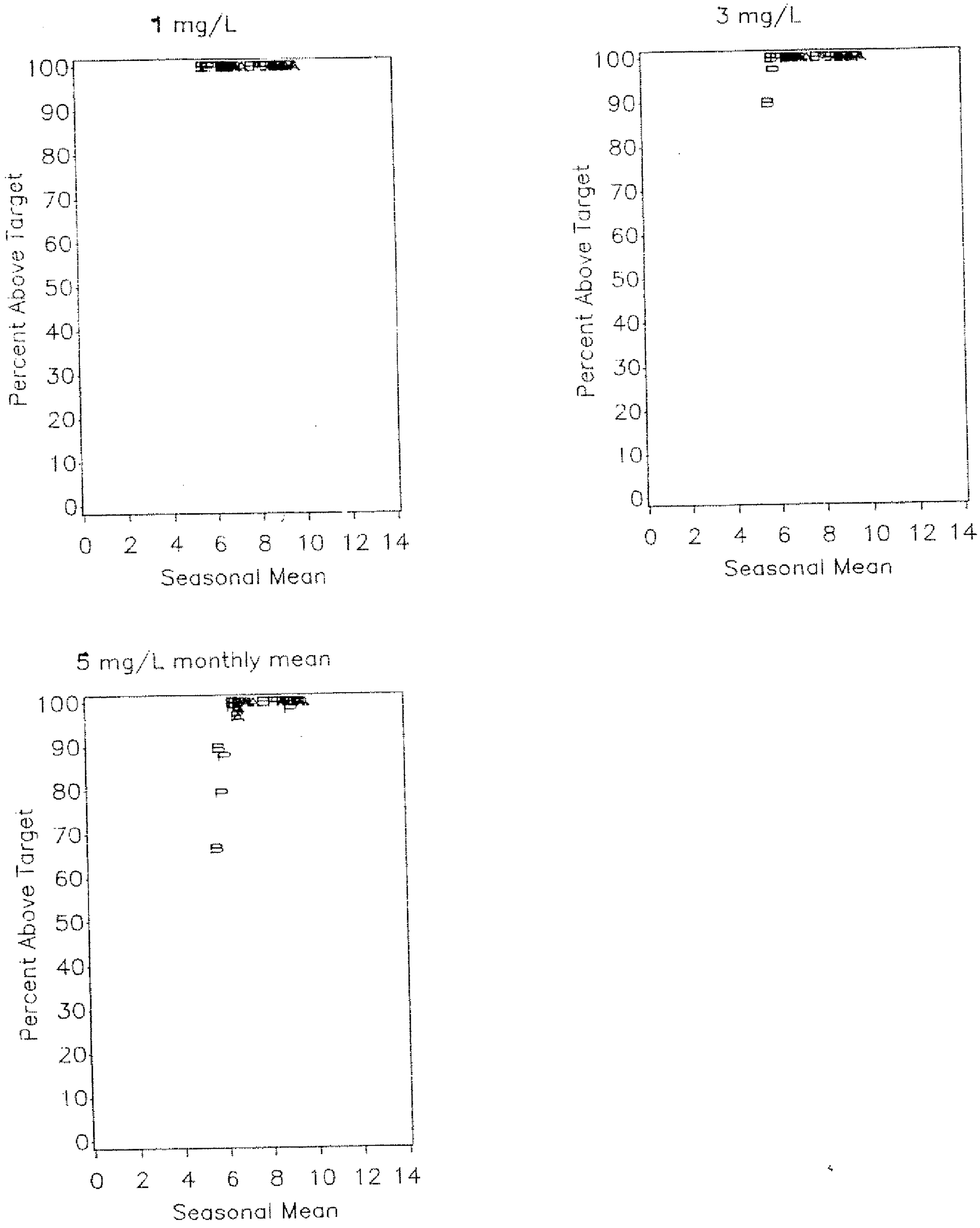

Figure B3-b7. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB[illegible] Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

B(3).b. Figures B3-b1 through B3-b8 present plots of the percent of Monitoring Program observations above target DO concentration (percent above target) versus annual seasonal mean DO concentration (seasonal mean), by mainstem CBP segments, for the years 1984 through 1990. Observations are grouped by segment, depth layer, season (spring and summer), and year. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline. Target DO concentrations are 1, 3, and 5 mg/L (instantaneous), and 5 mg/L monthly mean. The 5 mg/L target applies to anadromous fish spawning and nursery areas and therefore does not apply to CBP segments CB4 through CB8, and EE3.

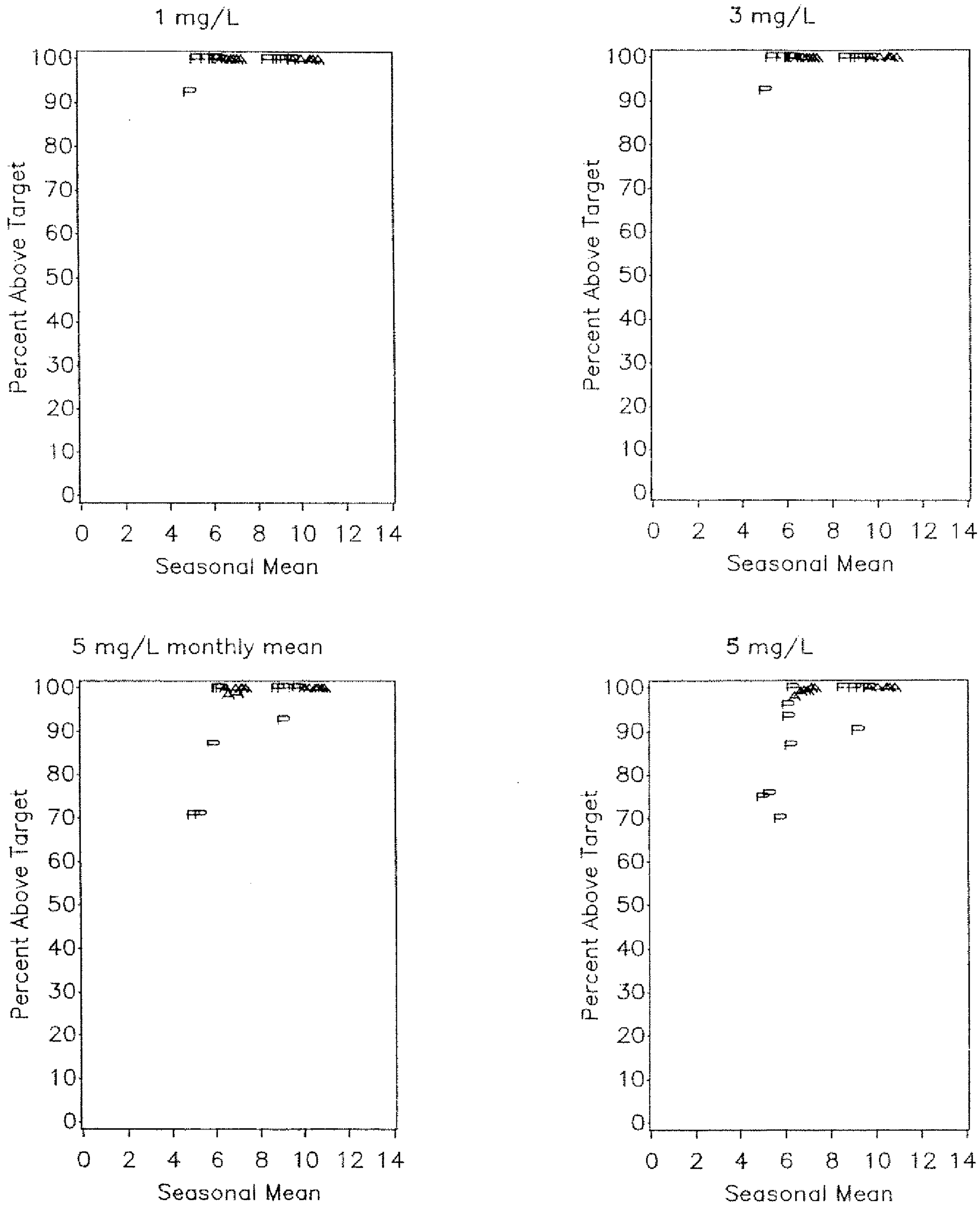

Figure B3-b1. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segments CB1-: Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnoclin P=region of the pycnocline, and B=below pycnocline.

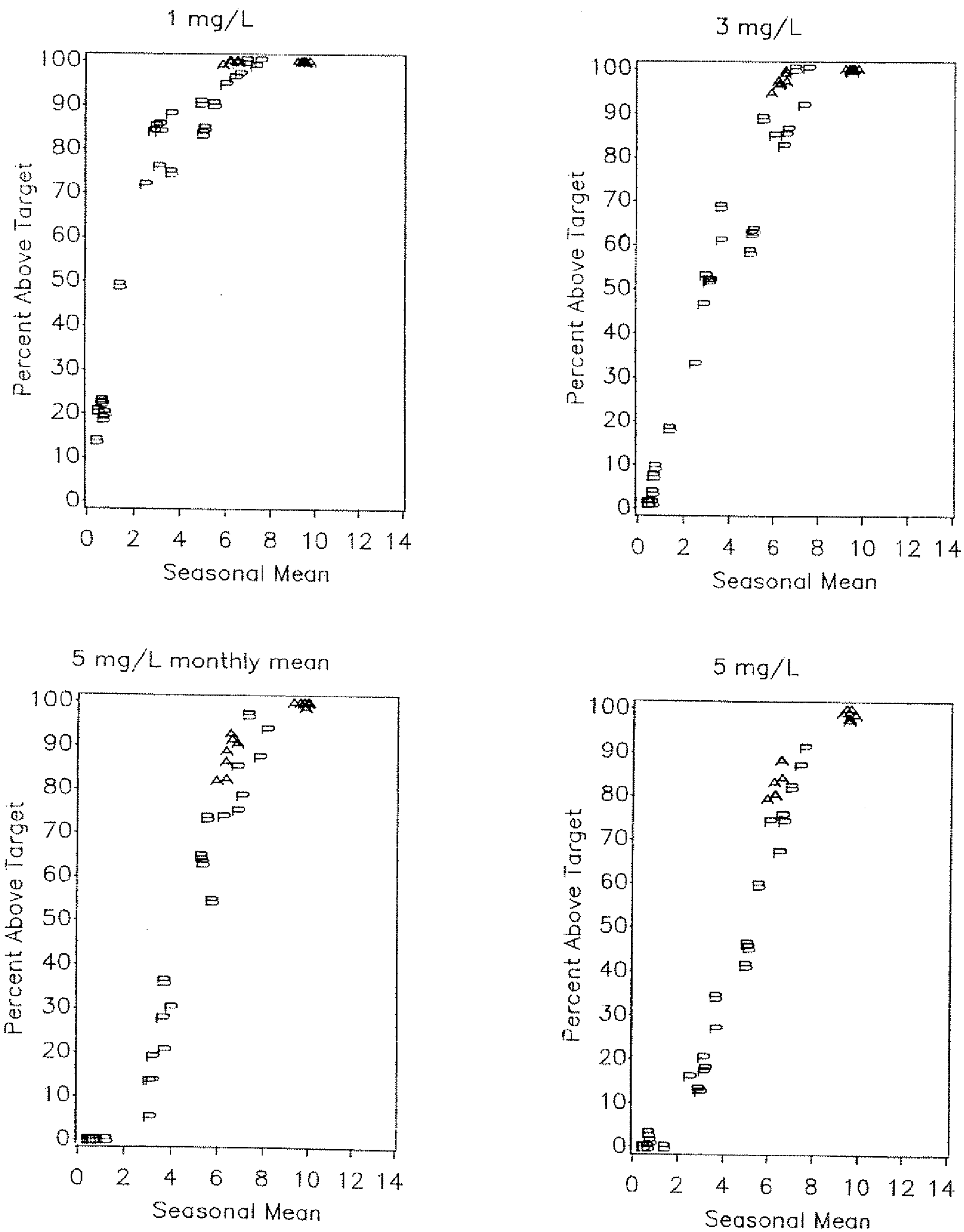

Figure B3-b2. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB3. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

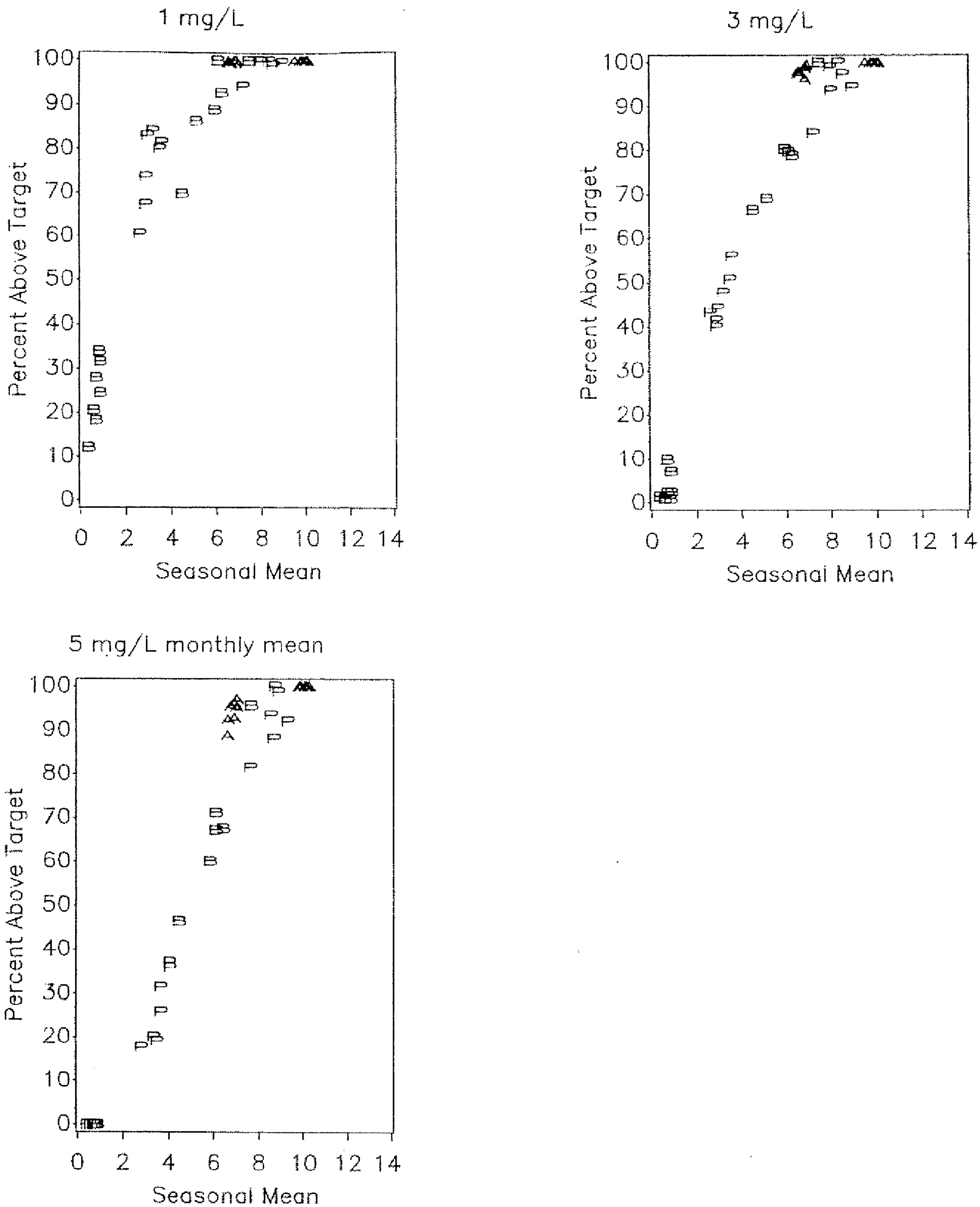

Figure B3-b3. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB4. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

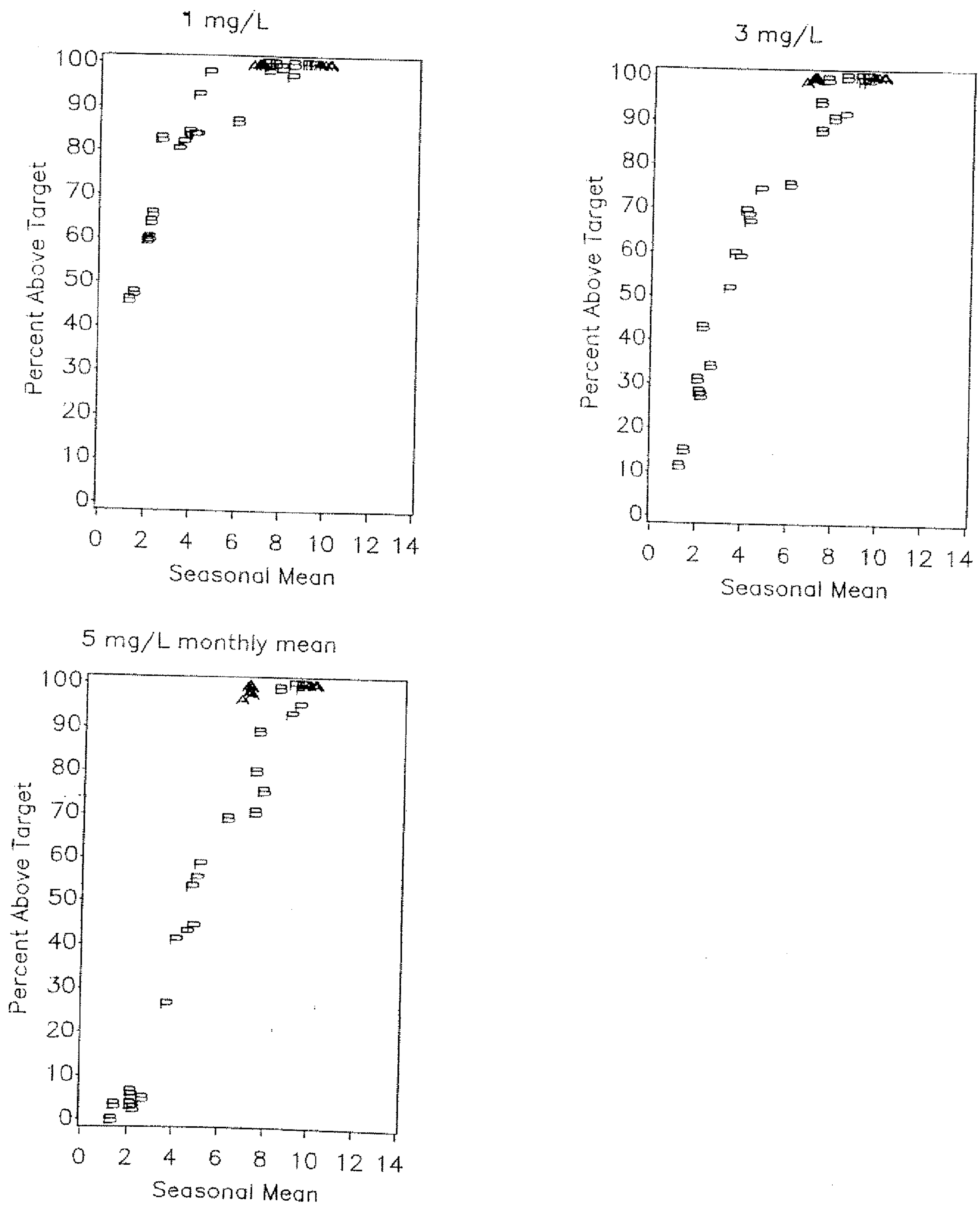

Figure B3-b4. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB5. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

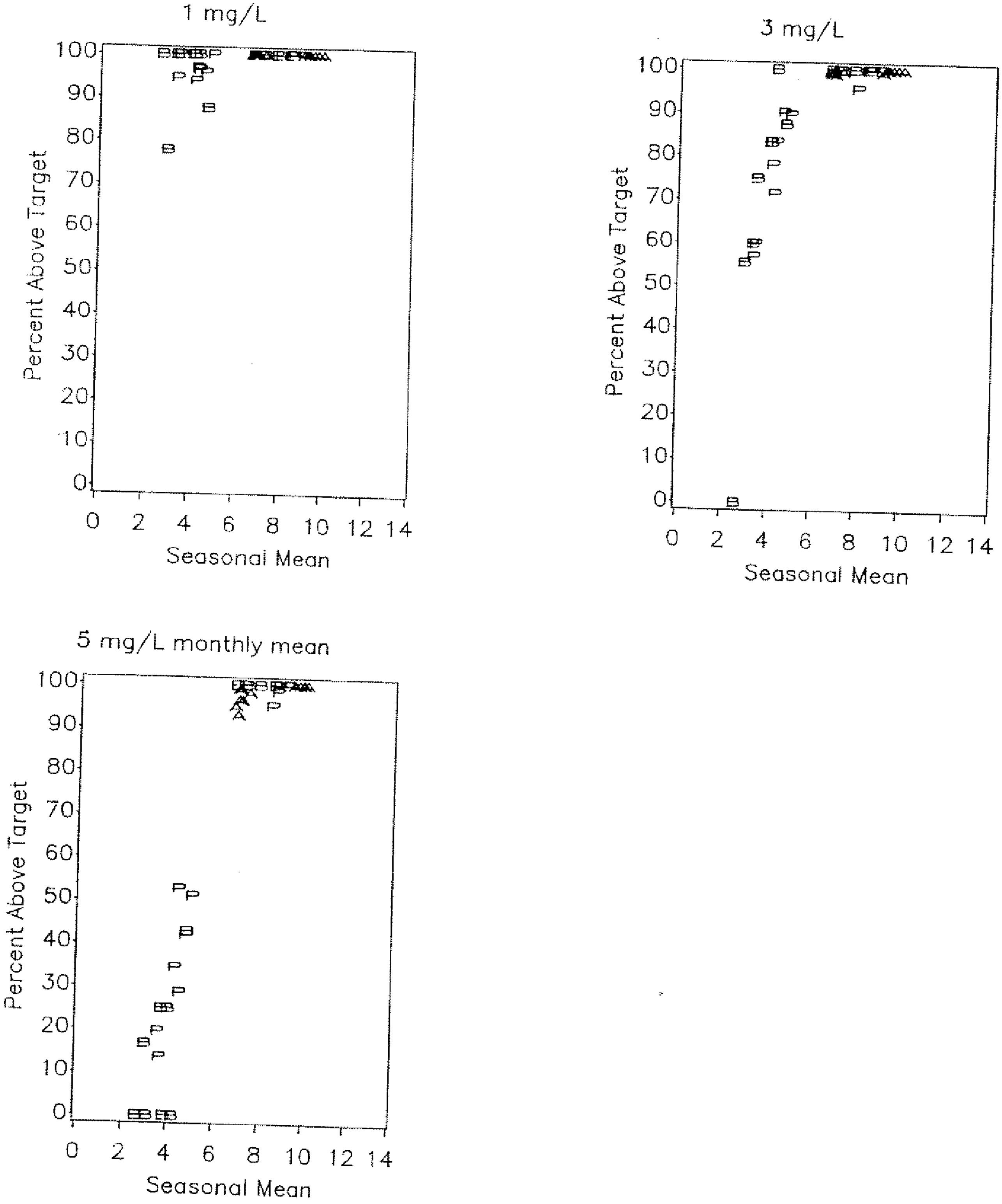

Figure B3-b5. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB6. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

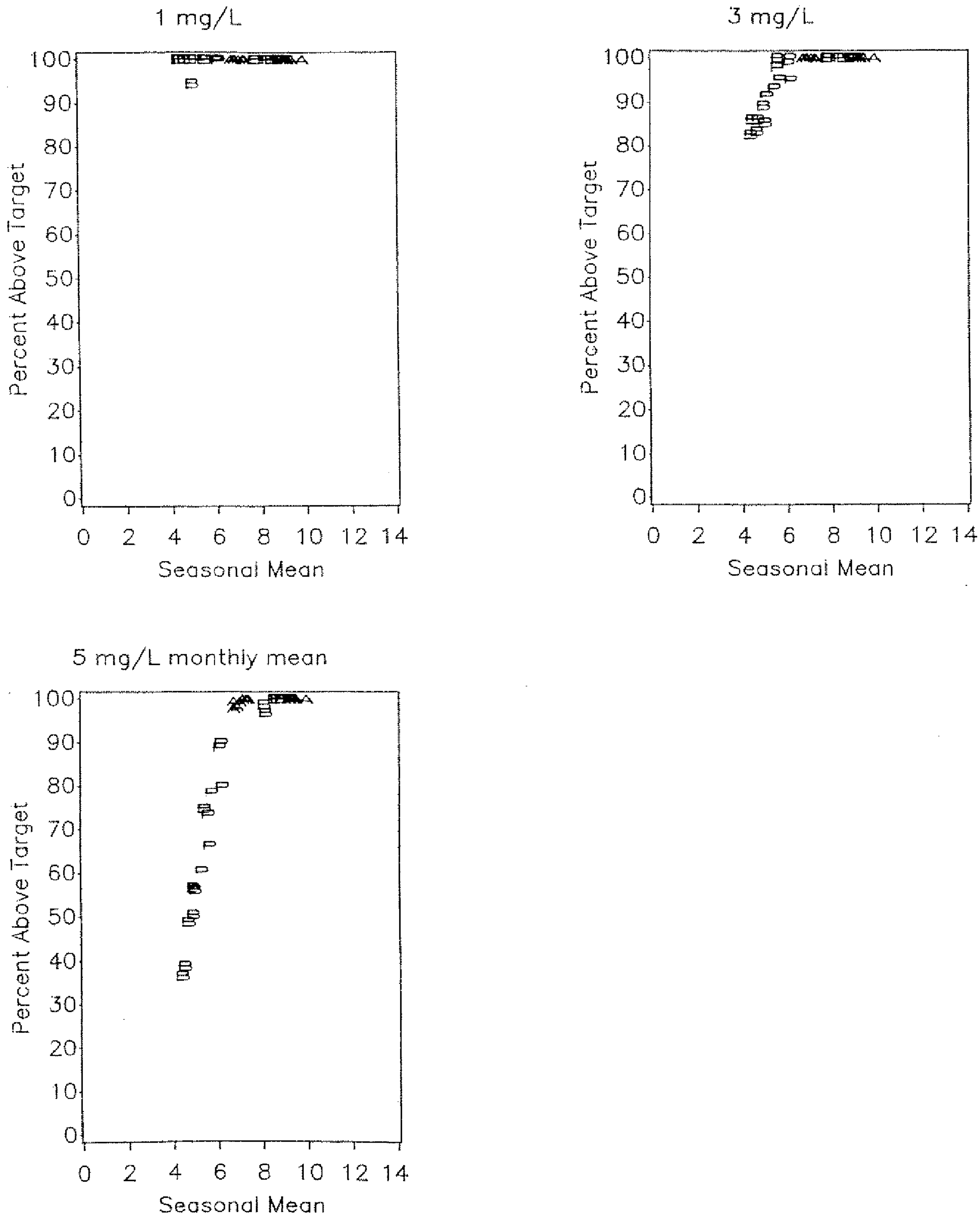

Figure B3-b6. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB7. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

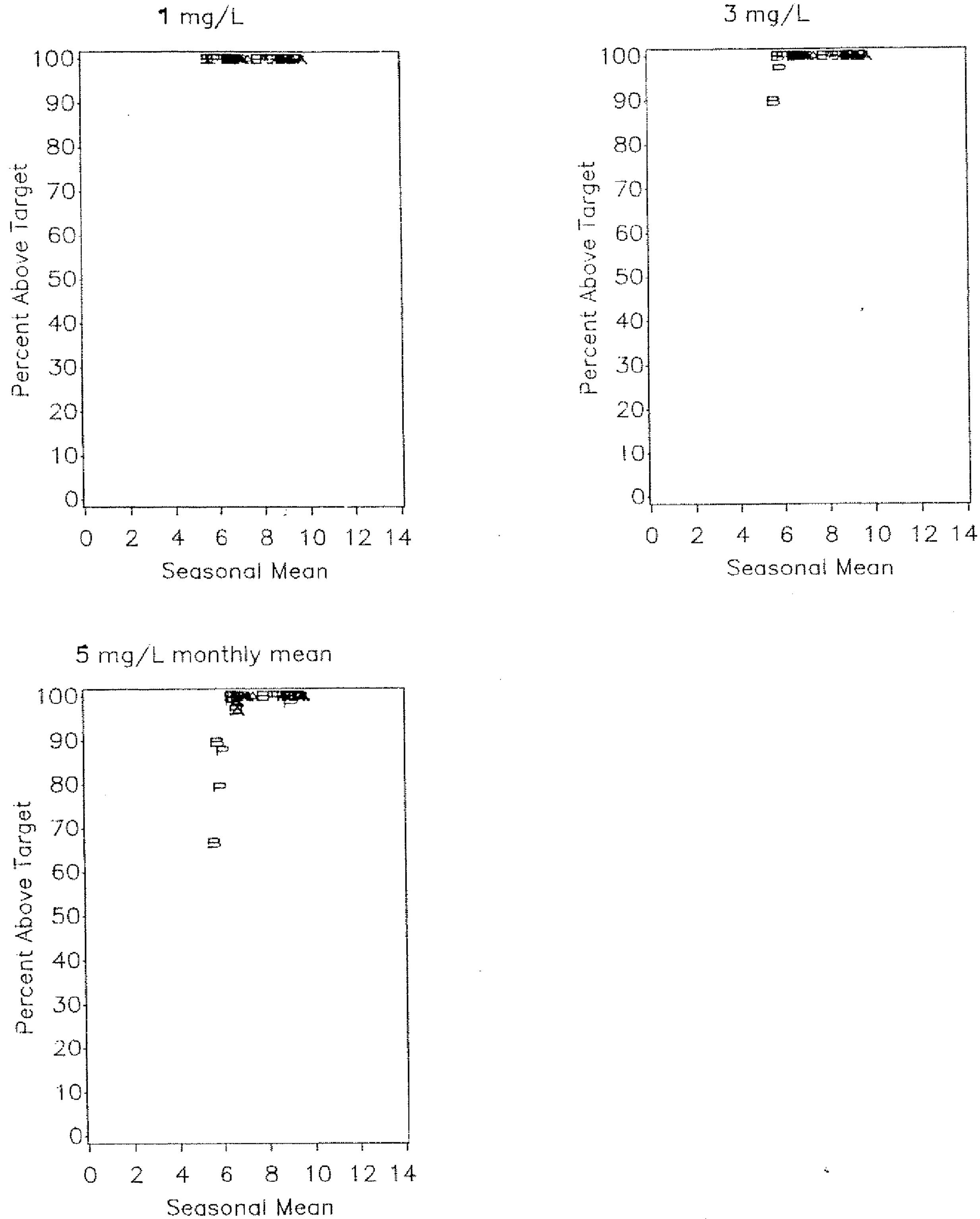

Figure B3-b7. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment CB8 Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline P=region of the pycnocline, and B=below pycnocline.

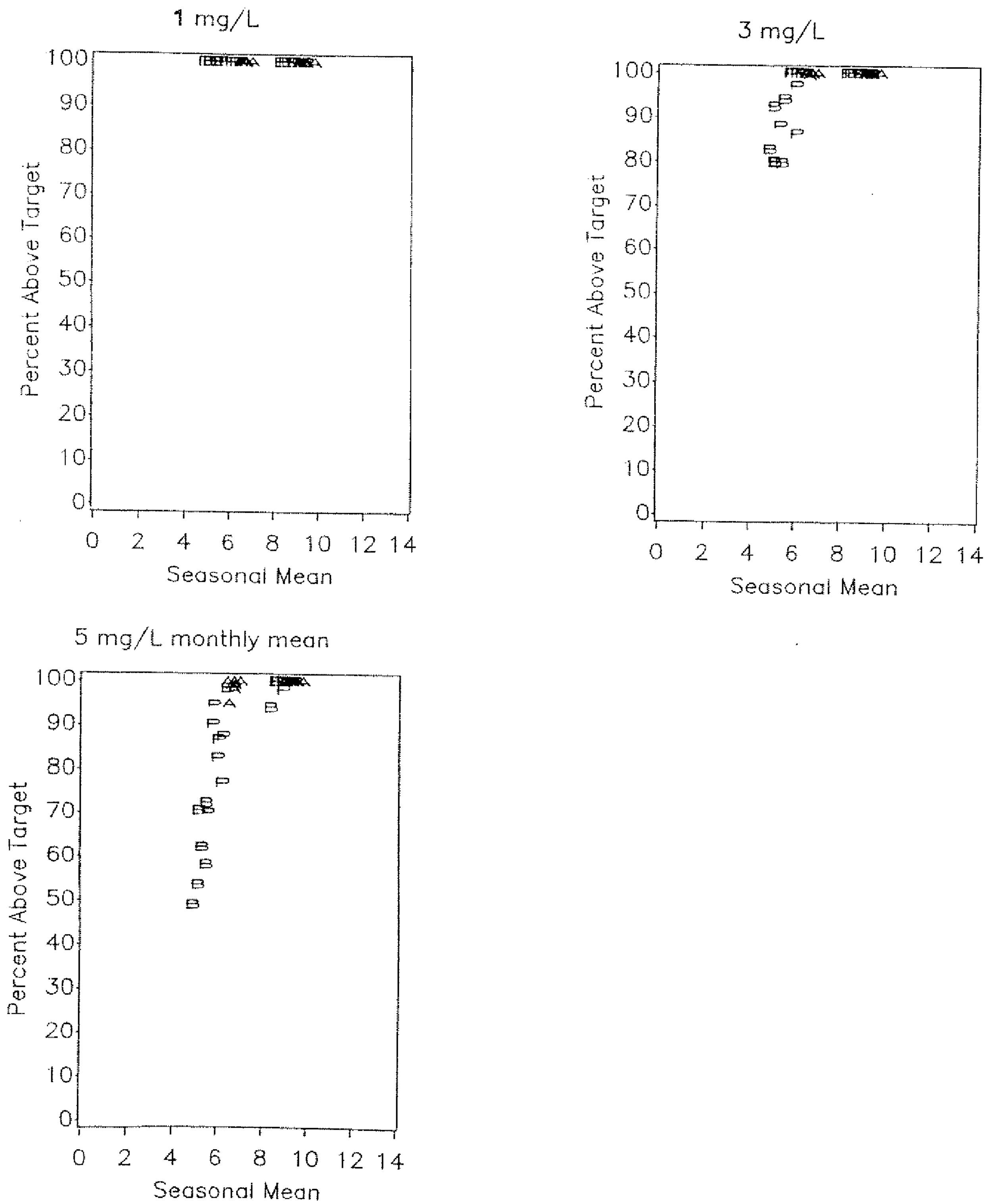

Figure B3-b8. Percent of observations above target concentration versus seasonal mean DO concentration (mg/L) within CBP segment EE3. Letter symbols indicate depth layer of the data from which the seasonal mean and percent of observations were calculated. A=above pycnocline, P=region of the pycnocline, and B=below pycnocline.

B4.(a). Regression coefficients and R-square values for the equation predicting the arcsine(square root of the ratio of the number of observations above the indicated target concentration to the total number of observations) as a function of seasonal mean DO within each mainstem model segment. The equation used in the regression analysis is:

$$\text{arcsine[sqrt(ratio)]} = A^*(\text{seasonal mean})^2 + B^*(\text{seasonal mean}) + C.$$

A. 1 mg/L target concentration

Model Segment	A	B	C	R-Square
1	-0.0336	0.4670	-0.0322	0.8854
2	-0.0156	0.2797	0.3024	0.9519
3	-0.0143	0.2661	0.3366	0.9324
4	-0.0150	0.2613	0.4114	0.9070
5	-0.0148	0.2520	0.4954	0.8820
6	0.0023	-0.0037	1.4497	0.3518
7	0.0000	0.0000	1.5708	.
8	0.0000	0.0000	1.5708	.
9	0.0085	-0.1086	1.8650	0.1262

B. 3 mg/L target concentration

Model Segment	A	B	C	R-Square
1	-0.0250	0.4360	-0.3392	0.7041
2	-0.0130	0.2819	0.0128	0.9477
3	-0.0130	0.2904	-0.0473	0.9563
4	-0.0155	0.3153	-0.0718	0.9428
5	-0.0146	0.3121	-0.0451	0.9442
6	-0.0251	0.4082	-0.1103	0.7821
7	0.0000	0.0000	1.5708	.
8	-0.0495	0.7801	-1.4466	0.5729
9	-0.0444	0.7090	-1.2260	0.8601

C. 5 mg/L monthly mean concentration

Model Segment	A	B	C	R-Square
1	-0.0299	0.5746	-1.2151	0.7266
2	-0.0068	0.2420	-0.1802	0.9700
3	-0.0070	0.2436	-0.1779	0.9564
4	-0.0091	0.2791	-0.2892	0.9322
5	-0.0187	0.4147	-0.7257	0.9104
6	-0.0524	0.9096	-2.3889	0.9720
7	-0.1111	1.7381	-5.1132	0.8182
8	-0.1220	1.9405	-6.0291	0.7472
9	-0.0678	1.1203	-3.0530	0.9071

D. 5 mg/L target concentration for anadromous fish spawning and nursery areas.

Model Segment	A	B	C	R-Square
1	-0.0221	0.4572	-0.8170	0.8128
2	-0.0040	0.2012	-0.0690	0.9725

B4.(b). Regression coefficients and R-square values for the equation predicting the arcsine(square root of the ratio of the number of observations above the indicated target concentration to the total number of observations) as a function of seasonal mean DO within each mainstem CBP segment. The equation used in the regression analysis is

$$\text{arcsine}[\text{sqrt}(\text{ratio})] = A^*(\text{seasonal mean})^2 + B^*(\text{seasonal mean}) + C.$$

A. 1 mg/L target concentration

CBP Segment	A	B	C	R-Square
CB1	-0.0267	0.4185	-0.0032	0.4958
CB2	-0.0267	0.4185	-0.0032	0.4958
CB3	-0.0164	0.2864	0.3216	0.9425
CB4	-0.0148	0.2682	0.3367	0.9418
CB5	-0.0136	0.2463	0.4455	0.9255
CB6	0.0054	-0.0237	1.4398	0.1915
CB7	0.0088	-0.1093	1.8599	0.1056
CB8	0.0000	0.0000	1.5708	.
EE3	0.0000	0.0000	1.5708	.

B. 3 mg/L target concentration

CBP Segment	A	B	C	R-Square
CB1	-0.0267	0.4185	-0.0032	0.4958
CB2	-0.0267	0.4185	-0.0032	0.4958
CB3	-0.0124	0.2797	0.0179	0.9443
CB4	-0.0126	0.2831	-0.0131	0.9596
CB5	-0.0150	0.3068	-0.0280	0.9284
CB6	-0.0527	0.7459	-1.0806	0.8094
CB7	-0.0362	0.5790	-0.7240	0.8795
CB8	-0.0460	0.7254	-1.2357	0.5625
EE3	-0.0567	0.8950	-1.9027	0.7004

C. 5 mg/L monthly mean concentration

CBP Segment	A	B	C	R-Square
CB1	-0.0419	0.7127	-1.4039	0.5003
CB2	-0.0419	0.7127	-1.4039	0.5003
CB3	-0.0056	0.2367	-0.2001	0.9646
CB4	-0.0072	0.2490	-0.1964	0.9622
CB5	-0.0142	0.3432	-0.4664	0.9137
CB6	-0.0357	0.6865	-1.6835	0.8888
CB7	-0.0591	1.0013	-2.6720	0.9506
CB8	-0.1075	1.7198	-5.2148	0.7551
EE3	-0.0813	1.3241	-3.7892	0.8234

D. 5 mg/L target concentration for anadromous fish spawning and nursery areas.

CBP Segment	A	B	C	R-Square
CB1	-0.0434	0.7533	-1.6714	0.6421
CB2	-0.0434	0.7533	-1.6714	0.6421
CB3	-0.0041	0.2112	-0.1336	0.9709

B5.(a). Minimum seasonal mean DO concentration (mg/L), by model segment, required to achieve the DO restoration goal, i.e. 99% of observations will equal or exceed the specified target concentration. (-) not applicable.

	Target Concentration			
Model Segment	1 mg/L[a]	3 mg/L[b]	5 mg/L[c]	5 mg/L[d]
1	5.1	6.8	8.5	8.0
2	6.6	8.5	9.4	9.2
3	6.6	8.3	-	9.2
4	6.4	8.2	-	8.9
5	6.0	7.4	-	8.8
6	4.0[e]	6.4	-	7.4
7	5.2[e]	5.2	-	6.4
8	5.7[e]	6.1	-	6.6
9	4.5[e]	6.2	-	7.0

[a] Applied at all times to all depths.
[b] Applied at all times to all depths. The seasonal mean DO concentrations shown do not take into account the duration and return frequency of excursions between 1 and 3 mg/L allowed under this goal component. The seasonal mean required to attain the formal goal component would be lower than the concentrations shown here.
[c] Applied at all times above the pycnocline in anadromous fish spawning and nursery habitats.
[d] Applied above the pycnocline (monthly mean).
[e] Dissolved oxygen never, or rarely, went below the target concentration in this segment. The seasonal mean shown is the lowest seasonal mean recorded in any depth category with 100% of the observations above the target concentration.

B5.(b). Minimum seasonal mean DO concentration (mg/L), by model segment, required to achieve the DO restoration goal, i.e. 99% of observations are above the applicable target concentrations.

Model Segment	Below Pycnocline	Above Pycnocline
1	5.1[a]	8.5[b]
2	6.6[a]	9.4[b]
3	6.6[a]	9.2[c]
4	6.4[a]	8.9[c]
5	6.0[a]	8.8[c]
6	4.0[a,d]	7.4[c]
7	5.2[a,d]	6.4[c]
8	5.7[a,d]	6.6[c]
9	4.5[a,d]	7.0[c]

[a] Controlling target concentration is 1 mg/L
[b] Controlling target concentration is 5 mg/L
[c] Controlling target concentration is 5 mg/L monthly mean
[d] Dissolved oxygen never, or rarely, went below the target concentration in this segment. The seasonal mea shown is the lowest seasonal mean recorded in any depth category with 100% of the observations above the targ concentration.

B5.(c). Minimum seasonal mean DO concentration (mg/L), by CBP segment, required to achieve the DO restoration goal, i.e. 99% of observations will equal or exceed the specified target concentration. (-) not applicable.

	Target Concentration			
CBP segment	1 mg/L[a]	3 mg/L[b]	5 mg/L[c]	5 mg/L[d]
CB1	5.3	5.3	7.0	6.6
CB2	5.3	5.3	7.0	6.6
CB3	6.3	8.1	9.2	8.9
CB4	6.7	8.4	-	9.1
CB5	6.5	8.1	-	9.0
CB6	3.3[e]	5.8	-	7.6
CB7	4.4[e]	6.2	-	7.2
CB8	5.6[e]	6.0	-	6.7
EE3	4.9[e]	6.2	-	6.9

[a] Applied at all times to all depths.
[b] Applied at all times to all depths. The seasonal mean DO concentrations shown do not take into account the duration and return frequency of excursions between 1 and 3 mg/L allowed under this goal component. The seasonal mean required to attain the goal component as actually defined would be lower than the concentrations shown here.
[c] Applied at all times above the pycnocline in anadromous fish spawning and nursery habitats.
[d] Applied above the pycnocline (monthly mean).
[e] Dissolved oxygen never, or rarely, went below the target concentration in this segment. The seasonal mean shown is the lowest seasonal mean recorded in any depth category with 100% of the observations above the target concentration.

B5.(d). Minimum seasonal mean DO concentration (mg/L), by CBP segment, required to achieve the DO restoration goal, i.e. 99% of observations are above the applicable target concentrations.

CBP Segment	Below Pycnocline	Above Pycnocline
CB1	5.3[a]	7.0[b]
CB2	5.3[a]	7.0[b]
CB3	6.3[a]	9.2[b]
CB4	6.7[a]	9.1[c]
CB5	6.5[a]	9.0[c]
CB6	3.3[a,d]	7.6[c]
CB7	4.4[a,d]	7.2[c]
CB8	5.6[a,d]	6.7[c]
EE3	4.9[a,d]	6.9[c]

[a] Controlling target concentration is 1 mg/L
[b] Controlling target concentration is 5 mg/L
[c] Controlling target concentration is 5 mg/L monthly mean
[d] Dissolved oxygen never, or rarely, went below the target concentration in this segment. The seasonal mean shown is the lowest seasonal mean recorded in any depth category with 100% of the observations above the target concentration.

B6.(a). Steps for Determining the Status of Water Quality Relative to the Dissolved Oxygen Restoration Goal from Time-Variable Model Output

To calculate Percentage Achievement:

1. Obtain the estimate of the seasonal mean dissolved oxygen concentration for the particular model cell of interest. Model results are seasonal mean DO concentrations. Seasonal mean concentrations are estimated for each of several thousand model cells. For this application, the four seasons are defined as follows: winter includes January and February; spring, March through May; summer, June through September; and fall, October through December.

Example: summer mean DO concentration = 5.5 mg/L

2. Identify the model segment and depth layer to which the model cell belongs. For purposes of the time-variable model, the Bay is divided, in planar view, into nine segments (Segments 1-9, Figure IV-4). Model estimates for each cell are related to the location of the cell above, at, or below arbitrary depth boundaries. Surface to 6.7 m is defined as the region above the pycnocline, 6.8 m to 12.7 m is the region of the pycnocline, and greater than 12.7 m is the region below the pycnocline. For this application, model cells above 6.7 m (cell layers 1 through 4) are considered above pycnocline and model cells below 6.7 m (cell layers 5 through 14) are considered below pycnocline.

Example: model segment #2, below pycnocline

3. Identify the controlling goal component relevant to the model segment and depth layer [Table IV-7 or Appendix Table B5.(b)]. Note that the 3 mg/L target concentration cannot be applied in this context.

Example: the 1 mg/L target concentration is controlling for below pycnocline cells in model segment 2. The minimum seasonal mean DO required for 99% achievement is 6.6 mg/L.

4. Compute the value for T in equation (a) below.

(a) $T = A^*(\text{conc})^2 + B^*(\text{conc}) + C$, where

T = predicted arcsine transformation of the square root of the ratio of the number of observations above target concentration to the total number of observations;

conc = the mean dissolved oxygen concentration for the cell obtained in step 1, above; and,

A, B, and C are the regression coefficients specific to the relevant goal component determined in step 3, above, and found in Appendix Table B4.(a).

Example: $T = (-0.0156 \times 5.5^2) + (0.2797 \times 5.5) + 0.3024 = 1.3689$

5. Compute the Percentage Achievement (percent above target) using equation (b) below, where the percent above target is obtained by back transforming the result of step 4; i.e, by taking sine(T), squaring the result, then multiplying by 100.

(b) Percent Achievement = $[\text{sine}(T)]^2 \times 100$.

Example: $Pct = [\text{sine}(1.3689)]^2 \times 100 = (0.9797)^2 \times 100 = 96\%$ (rounded to nearest percent)